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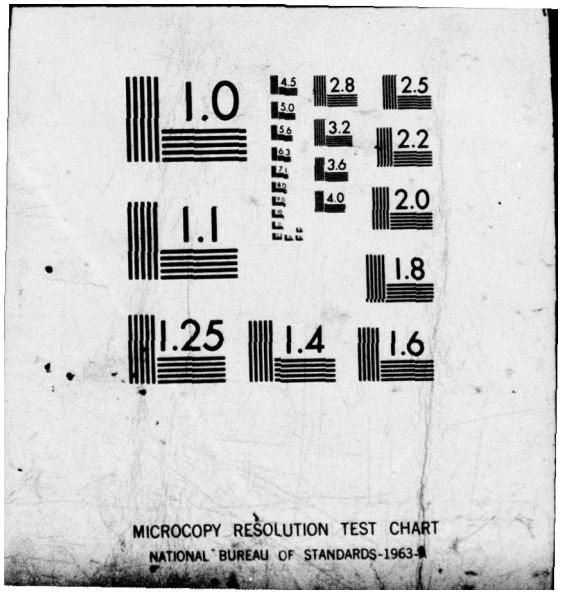
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REVISED MODEL OF THE PERIPHERAL AUDITORY SYSTEM THROUGH PRIMARY AUDITORY NERVE

Duane G. Leet, PhD

University of Dayton Research Institute
300 College Park Avenue
Dayton, Ohio 45469

June 1977

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A model of the auditory system from the middle ear through primary auditory nerve has been developed. The components of the model are an electronic analog device that generates the middle ear and cochlear transfer functions and two sets of FORTRAN routines that realize the absolute magnitude transformation of the entire peripheral auditory system and the primary auditory nerve transformation.

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It is found that the model's spontaneous and pure tone behavior, measured in terms of Pulse Occurrence and Pulse Interval Histograms, correlates well with the neuron's behavior. The neuron and model vowel Pulse Occurrence and Pulse Interval Histograms of the vowels /ɛ/, /æ/, /i/, /ɔ/, and /I/ correlate favorably. There is some question about the similarity of the neuron and model vowel Pulse Occurrence Histograms for the vowel /ɹ/.

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FOR THE COMMANDER

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Director
Biodynamics and Bionics Division
Aerospace Medical Research Laboratory

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It is found that the model's spontaneous and pure tone behavior, measured in terms of Pulse Occurrence and Pulse Interval Histograms, correlates well with the neuron's behavior. The neuron and model vowel Pulse Occurrence and Pulse Interval Histograms of the vowels /ɛ/, /æ/, /i/, /ɔ/, and /I/ correlate favorably. There is some question about the similarity of the neuron and model vowel Pulse Occurrence Histograms for the vowel /ɚ/.

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Two modifications to this final model iteration are considered: Using a different cochlea channel and modifying the middle ear circuit. It is concluded that neither modification would be cost effective.

Information generated from this study will be incorporated into the development of speech recognition systems based upon the performance characteristics of the auditory system. Such systems would be a valuable tool to the Air Force in the fields of intelligence, communications, and man-machine interface.

SUMMARY

A model of the peripheral auditory system, up to and including the primary auditory nerve, is in an advanced stage of development. The model is comprised of an analog electronic device, the ROC COC Analog Cochlea, that simulates the temporal and relative magnitude transform of the middle and inner ear, and a FORTRAN program system that simulates the primary auditory nerve and the absolute magnitude transform of the entire peripheral auditory system.

Originally, the ROC COC's middle ear circuit was an active bandpass filter with a center frequency of about 1.8 kHz, a bandwidth of about 3 kHz, a low frequency skirt with a 6 dB/octave slope, and a high frequency skirt with a 100 dB/octave slope.

The ROC COC's cochlea section is a transmission line comprised of a cascade of lowpass filters. Each filter is tapped to provide an output voltage analogous to the displacement at a point on the cochlea's basilar membrane.

The first software segment in the processing sequence is called the Transducer Module (TM) and it computes the absolute magnitude transform of the model. It is not intended to represent any one component of the peripheral auditory system.

The model of the primary auditory nerve is called the Basic Stochastic Syncoder. It is a binary threshold device with the threshold function $F(i\Delta) = \varphi + \theta \exp[B \cdot (j-i)\Delta]$, where B is a random variable called the decay rate, with probability density function $p_B(\cdot)$, j is the time interval when the syncoder last fired, Δ is the sample interval, and φ and θ are parameters. The threshold function is compared at each time interval with the syncoder's summation potential $q(i\Delta) = \min\{\alpha_x \cdot x(i\Delta - \tau_x \Delta), q_{max}\}$, where $x(\cdot)$ is the syncoder's stimulus and q_{max}, α_x, and τ_x are parameters. At any sample interval, except those falling within the syncoder's absolute refractory period, the syncoder will generate a one (1) response if the threshold function value is not greater than the summation potential value:

$$Y(i\Delta) = \begin{cases} 1 \text{ iff } q(i\Delta) \geq F(i\Delta) \text{ and } i-j > \rho/\Delta \\ 0 \text{ otherwise} \end{cases}$$

where ρ is the absolute refractory period. At that instant the threshold function is reset to its maximum value, a new decay rate value B is chosen according to $p_B(\,.\,)$, and the threshold function begins its decay.

In earlier neurophysiological experiments pure-tone stimuli and speech-like stimuli comprised of sequences of five vowel sounds were presented to the middle ear of guinea pigs and the response of the primary auditory neurons recorded. These data are the standard of comparison for the model's development and verification.

Both theoretical and empirical studies of the model's behavioral characteristics were performed. From these studies procedures were developed for estimating the model's parameter values from the available neurophysiological data.

Five different parameter value sets were used to provide five model candidates whose behavior was compared to a 1263 Hz CF primary neuron.

Pure-tone and speech-like stimuli originally presented to the neuron were presented to each of the five models. Selection of the best model was based on a qualitative evaluation of PIH shapes and a quantitative analysis of the number of peaks that matched between corresponding model and neuron vowel - Pulse Interval Histograms. (A vowel-PIH is a Pulse Interval Histogram constructed from the segment of responses corresponding to a single vowel in the stimulus.)

The best model was presented with several more pure-tone and speech-like stimuli previously presented to the neuron. Corresponding vowel-PIHs of the model and neuron generated from the responses to these stimuli were compared using a "fraction of misplaced peaks" metric. Using benchmark values obtained by comparing different neuron vowel-PIHs generated from responses to approximately the same intensity, it was determined that the

model produced vowel-PIHs that fell within the benchmark for six or seven of the ten vowel sounds used.

Close scrutiny of the vowel-PIH results, along with an evaluation of the differences between neuron and model vowel-POHs*, led to a modification of the TM transfer function. The new model was presented with the same set of stimuli as before, and the responses evaluated in the same way. There was an improvement in the results, but a further modification was suggested: the slope of the middle ear circuit's low frequency skirt was changed from 6 dB/octave to 12 dB/octave. The new hardware component was called ROC COC2.

This report presents an evaluation of the behavior of this model in response to the same set of stimuli. It is found that the neuron and model vowel-POHs of the vowels /ɛ/, /æ/, /i/, /ɔ/, and /I/ correlate favorably. There is some question about the similarity of the neuron and model /ɚ/ - POHs. The neuron and model vowel-POHs where there is a problem in the correlation were /ə/, /a/, /o/, and /u/. In all cases the neuron vowel-POHs have extra peaks in them that are absent or not present in sufficient magnitude to produce corresponding peaks in the model vowel-POHs.

Two modifications to the model are considered; using a different ROC COC2 response channel and modifying the middle ear circuit. It is concluded that neither modification would be cost-effective.

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* Pulse Occurrence Histograms

PREFACE

This is the final report on work performed under Contract F33615-76-C-0510, Work Unit 2312V415, "Specific Signal Analysis Techniques Employed by the Auditory System", University of Dayton Research Institute (UDRI), Dayton, Ohio; Dr. Duane G. Leet, Principal Investigator.

The entire program was conducted in support of Project No. 2312, Task 2312V4, "Applications of Basic Biological Principles and Mechanisms to Operation and Design of Air Force Systems" administered by the Neurophysiology Branch of the Aerospace Medical Research Laboratory, Wright-Patterson Air Force Base, Ohio. The period covered is 1 February 1976 to 28 February 1977. Dr. Thomas J. Moore was the initiator and monitor of this research.

Air Force support of this program is justified by the following arguments. First, the human auditory system is a speech processing system that far surpasses current technological capabilities. Study of this system from a rigorous information-theoretic viewpoint could lead to improvement of existing technology or development of an entirely new technology that can be used by the Air Force in intelligence, reconnaissance, air traffic control, air mission control, and man-machine interface. Second, the voiced speech signal is comprised of a sequence of glottal pulses. Mathematically, a glottal pulse can be considered to be a short sample of a Fourier transformable Function embedded in noise. This noise comes from two sources. The statistics of one source can vary with time but are independent of the glottal pulse. The statistics of the other source depends on the sequence of glottal pulses preceding the given pulse; that is, the glottal pulse frequency characteristics are context-sensitive. The human auditory system is able, therefore, to recognize sequences of context sensitive signals embedded in noise, and to do this in real time. Again, the capabilities of this system far surpass current technological capabilities to process such signals. The development of electronic systems with

these capabilities would have application both to the general signal recognition problem in Air Force intelligence and to electronic warfare.

In addition to this report, another report and paper were published using the support of this contract:

Leet, Duane G., "A Model of the Auditory System from the Middle Ear Through Primary Auditory Nerve", Proceedings of the 29th Annual Conference on Engineering in Medicine and Biology, Boston, 1976.

Moore, Thomas J., and John L. Cashin, Jr., "Response Patterns of Primary-Like" Cochlear Nucleus Neurons to Excerpts from Sustained Vowels", AMRL-TR-77-10, Aerospace Medical Research Laboratory, Wright-Patterson Air Force Base, Ohio, 1977.

The author expresses his sincere appreciation to Dr. Moore and to John L. Cashin, Jr., and Diana Esch of UDRI for their invaluable assistance.

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SECTION 1
INTRODUCTION

A model of the behavior of primary auditory neuron 710827/11 is being developed through iterations on the following basic procedure:

1. Estimated parameter values.
2. Run simulations.
3. Compare model and neuron behaviors.
4. Accept the model or make recommendations for model and/or parameter modification.

Figure 1 is the block diagram for this model. The cochlear filter component is a hardware analog of the middle and inner ears. The BSS, or Basic Stochastic Syncoder, exists in both hardware and software forms and is a model of the primary auditory neuron. The TM, or Transducer Module, currently exists in software and performs a log transformation between the cochlear filter output and the BSS input. See Leet (1976) for a detailed account of these components.

Procedures are detailed in Leet (1976) for estimating the parameter values of the model given the selected primary auditory neuron's spontaneous activity and responses to pure tone and speech-like stimuli.

In the first simulation iteration, the model generated responses to pure tone stimuli. Pulse Occurrence Histograms (POHs) and Pulse Interval Histograms (PIHs) were computed from these responses and they compared favorably with the corresponding neuron POHs and PIHs.

In the second simulation iteration, the model generated responses to several Glot-1 stimuli presented at different intensities.* Vowel-PIHs** were computed from these responses and compared with corresponding vowel-PIHs from the neuron. In addition, vowel-POHs were computed

---

*A Glot-1 stimulus is comprised of five 40 msec segments. Each segment is five pitch period of a vowel from the set [/ɹ/, /a/, /æ/, /ɔ/, /ɪ/, /i/, /ɛ/, /u/, /o/, /ə/]with no vowel appearing more than once in a stimulus.

*A vowel-PIH is a PIH computed over a single vowel segment of a Glot-1 stimulus.

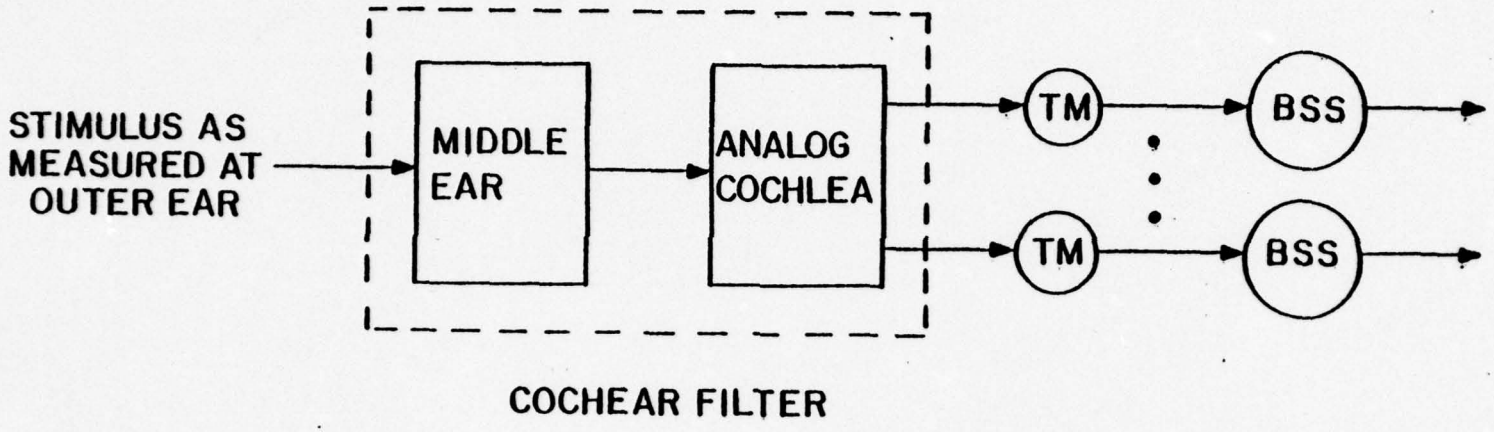


Figure 1. A Block Diagram of the Model.

from the model's responses and compared to the corresponding neuron vowel-POHs and the corresponding segments of the cochlear filter responses to the Glot-1 stimuli. The results reported in Leet (1976) suggested modifications to the TM. These modifications were made and a third simulation iteration performed . The data were analyzed as before and the results suggested a modification to the cochlear filter.

The complete model, with all the modifications made to date, is presented in Section 2. The Glot-1 stimuli were presented to this model and the usual analyses performed. The results are presented in Section 3. Section 4 concludes this report with a discussion of the results and recommendations for the next iteration of the modeling effort.

SECTION 2
MODEL 08/13/76

2.1 THE COCHLEAR FILTER COMPONENT ROC COC2

The first cochlear filter used in the modeling effort, which was called ROC COC, had the middle ear transfer function shown in Figure 2 as the curve marked with the dots. In earlier research on this program, there was evidence in the data generated by the models containing ROC COC that the effect of the second formant of the vowel /ṛ/ needed to be increased with respect to the effect of the first formant. This was accomplished by increasing the slope of the low frequency skirt of the middle ear transfer function by 6 dB/octave, shown in Figure 2 as the curve marked with the x's. The new cochlear filter is called ROC COC2.

2.2 THE TM COMPONENT

The transfer characteristic for the TM component of the model is shown in Figure 3. It is the one used for Model 06/29/76 in the third simulation effort.

2.3 THE BSS

The BSS parameter values in Table 1 are the same as used in the previous simulation iterations (Models 03/31/76 and 06/29/76).

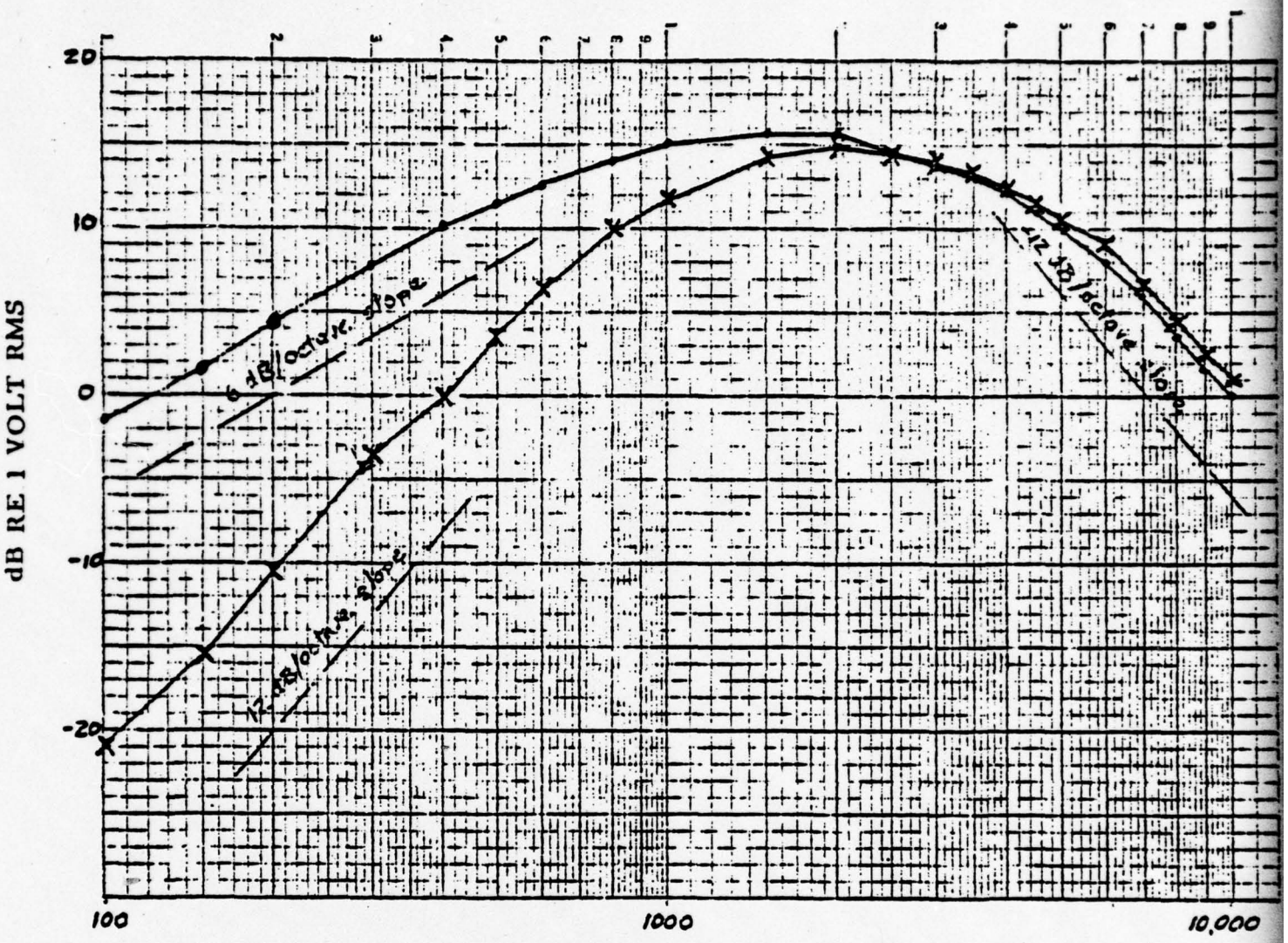


Figure 2. Bode Magnitude Plot of Middle Ear Transfer Function for ROC COC 2 Cochlear Filter. The Circuit Includes both the External and Internal Pre-Amps. The Curve Marked with the "X" Symbol is Obtained by Setting the Select Switch in the Velocity Position and is the Middle Ear Transfer Function for ROC COC 2. The Curve Marked with the "." Symbol is Obtained by Setting the Select Switch in the Displacement Position and is the Middle Ear Trarsfer Function for ROC COC.

dB	Value
100	60.46
67	60.46
55	120
45	126
35	126
30	128

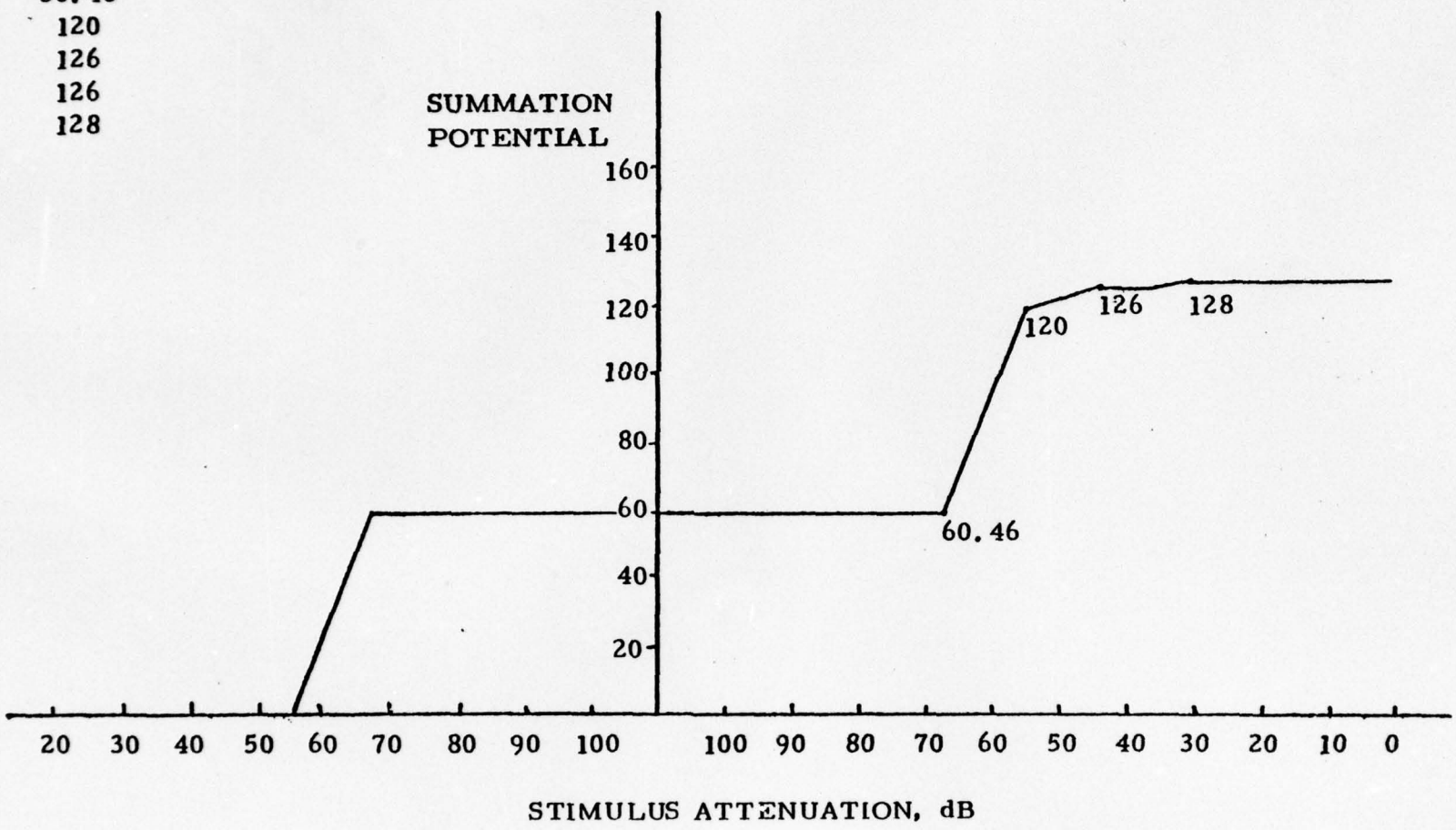


Figure 3. Transducer Module Transfer Function for Model 08/13/76.

TABLE 1

BSS PARAMETERS FOR MODEL 08/13/76

Low Average Interpulse Interval	6.89 msec
High Average Interpulse Interval	16.54 msec
θ	271.23
Bavg	.0908

SECTION 3
RESULTS

3.1 INTRODUCTION

The eight Glot-1 stimuli listed in Table 2 were presented to both the neuron and the model. Each of the ten vowels was presented four times: twice at an intensity of 10 dB attenuation, and once each at intensities of 20 and 40 dB attenuation. In this section the results from each vowel are analyzed as follows. First, the neuron vowel-POHs are juxtaposed with the corresponding model vowel-POHs and ROC COC2 response segments. A discussion of the time alignment problem is presented in Section 3.2. Then the four sets of curves are inspected for a common relationship between a pitch period of the ROC COC2 response segment and the corresponding segment of the neuron vowel-POH. The same inspection is performed for the model vowel-POH. If found, the common relationship is illustrated and discussed. In addition, the vowel-PIHs of the model and the neuron are presented and the Peak Occurrence Table computed. The Stimulus Interval Histograms are also presented. The text includes a discussion of any observations from these data that provide more insight into either the behavior of the neuron or how the neuron's behavior compares to that of the model.

3.2 THE ALIGNMENT PROBLEM

In order to compare the neuron vowel-POHs with the corresponding model vowel-POHs and the ROC COC2 response segments it was necessary to bring the three data sets into the proper absolute time alignment. The alignment of a model vowel-POH with its corresponding ROC COC2 response segment is trivial, since they are synchronized and based on the same clock (in the PDP-11). This is, however, not the case with the neuron vowel-POHs.

TABLE 2

LOG OF NEURON-MODEL RUN PAIRS

Glot-1 Stimulus			Run	
ID	Vowel Sequence	Intensity	Neuron 710827/11	Model 08/13/76
3A	/I/ /u/ /æ/ /a/ /ɛ/	10	6	08/13/76.1/1
3B	/ɔ/ /ɻ/ /i/ /o/ /ə/	10	7	08/13/76.1/2
4A	/ɛ/ /ə/ /a/ /o/ /æ/	40	8	08/13/76.1/3
4B	/i/ /u/ /ɻ/ /I/ /ɔ/	40	9	08/13/76.1/4
7A	/ɔ/ /I/ /ɻ/ /u/ /i/	10	14	08/13/76.2/1
7B	/æ/ /o/ /a/ /ə/ /ɛ/	10	15	08/13/76.2/2
8A	/ə/ /o/ /i/ /ɻ/ /ɔ/	20	16	08/13/76.2/3
8B	/ɛ/ /a/ /æ/ /u/ /I/	20	17	08/13/76.2/4

The Glot-1 stimuli were recorded on one channel of a two channel analog magnetic tape. The second channel contains a synch pulse at the beginning of each stimulus presentation. When the neural data were recorded, these synch pulses were used to trigger the acquisition of data by the PDP-1 system; When the ROC COC2 responses were recorded, they were used to trigger the acquisition of data by the PDP-11 system. The relative difference in the time required by the two systems to process the synch pulse was not known prior to the analysis of the data in this report. Furthermore, the ROC COC2 stimulus was delayed as it passed down the transmission line. This delay was about .9 msec. (five sample intervals) at the channel used for these experiments, channel 20. These two observations mean that, prior to the analysis reported here, the time origin of the neural POHs was shifted an unknown amount from the time origin of both the ROC COC2 responses and the model POHs.

The use of two different clocks further complicated the situation. From a preliminary comparison of neural and model vowel-POHs, it was apparent that the PDP-1 system clock was relatively faster than the PDP-11 system clock by about .2 to .4 msec per 40 msec. This tended to distort the comparison of the neuron and model vowel-POHs and forced a continual reassessment of the synchronization problem.

The first step in the procedure used to align the neuron vowel-POHs with the corresponding model vowel-POHs and ROC COC2 response segments was to visually compare the neuron and model vowel-POHs corresponding to the vowel segments of a stimulus. In all the stimuli except 8B, comparing the vowel-POHs of the first segment produced two candidate alignments. Generally each of these alignments forced an alignment on the succeeding neuron/model vowel-POH pair, and so on through the stimulus. As summarized in Table 3, four candidate alignments were proposed for the first vowel segment in stimulus 8B:

TABLE 3

CANDIDATE NEURON MODEL VOWEL-POH ALIGNMENTS FOR STIMULUS 8B

Vowel	CANDIDATE ALIGNMENTS				
Segment	I	II	III	IV	V
/ɛ/	as aligned	left shift (4)	left shift (8)	left shift (13)	
/a/		as aligned		left shift (5)	left shift (7)
/ae/		right shift (6)		as aligned	left shift (7)
/u/		right shift (7)		as aligned	left shift (11)
/I/		right shift (10)		as aligned	left shift (6)

(I) as aligned,

(II) left shift (4),

(III) left shift (8),

(IV) and (V) left shift (13).

The terminology is with respect to an arbitrary reference alignment. (In this case "(V) left shift (13)" is the alignment shown in Figure 36.) The numbers in parentheses are the number of sample intervals to shift with respect to the reference alignment. Two of these alignments, "(I) as aligned" and "(III) left shift (8)," produced poor visual correlations between model and neuron vowel-POHs in subsequent segments and were dropped from further consideration. The "(II) left shift (4)" alignment forced a "(II) as aligned" alignment on the next segment's vowel-POHs. The "(IV) left shift (13)" alignment forced two possible alignments on the second segment's vowel-POHs: "(IV) left shift (5)" and "(V) left shift (7)". (The reference alignment for the second segment was such that Figure 16a shows the "(IV) left shift (5)" alignment.) These alignments were forced on the vowel-POHs of the remaining segments to obtain the candidate alignments listed in Table 3. (In the last three segments of 8B "(IV) as aligned" was the reference alignment.)

The second step in the alignment procedure was to perform a visual correlation between the four available neuron vowel-POHs of the same vowel. There was often a clearly superior alignment between these vowel-POHs that restricted the possible alignments between the neuron and model vowel-POHs. For example, Table 4 lists the candidate neuron/model vowel-POH alignments for the vowel /ṛ/.

TABLE 4

CANDIDATE NEURON/MODEL /ṛ/ - POH ALIGNMENTS

STIMULUS	CANDIDATE ALIGNMENTS		
3B	as aligned	left shift (5)	
4B	as aligned		
7A	as aligned	right shift (3)	right shift (7)
8A	as aligned	right shift (4)	

Comparison of the neuron /ṛ/ - POHs suggested that there were only two possible neuron/model alignments that agreed with the clearly superior neuron /ṛ/ - POH alignment:

3B as aligned
4B as aligned
7A right shift (7)
8A right shift (4)

or

3B left shift (5)
4B as aligned
7A right shift (3)
8A as aligned

The third step in the alignment procedure was to compare the candidate alignments of the neuron/model vowel-POH pairs for best fit. A technique for quantitative evaluation of best fit was investigated during this step and found to be unsatisfactory. The technique was to form a sequence of the intervals between the (regional) minima between peaks, in units of sample intervals, for the entire neuron or model vowel-POH. This sequence was partitioned into subsequences corresponding to each of the vowel's pitch periods and arranged in matrix form. For instance, the sequence of intervals of the neuron /ɻ/ - POH in stimulus 3B, aligned as shown in Figure 4, was:

$$Na= \begin{bmatrix} & & & & & & & & 5 \\ 4 & 4 & 5 & 4 & 4 & 6 & 7 & 6 & 5 \\ 4 & 5 & 8 & & 3 & 7 & 7 & 5 & 6 \\ 3 & 4 & 4 & 5 & 4 & 6 & 7 & 5 & 7 \\ 3 & 4 & 4 & 5 & 3 & 7 & 6 & 7 & 5 \\ 3 & 5 & 4 & 4 & 4 & 6 & 7 & 6 & \end{bmatrix}$$

The sequence was arranged to create subsequences as close to the length of the pitch period (45 sample intervals) as possible. The matrix corresponding to the sequence of intervals shifted one peak (5 sample intervals) to the right was:

$$Ns= \begin{bmatrix} 5 & 4 & 4 & 5 & 4 & 4 & 6 & 7 & 6 \\ 5 & 4 & 5 & 2 & 6 & 3 & 7 & 7 & 5 \\ 6 & 3 & 4 & 4 & 5 & 4 & 6 & 7 & 5 \\ 7 & 3 & 4 & 4 & 5 & 3 & 7 & 6 & 7 \\ 5 & 3 & 5 & 4 & 4 & 4 & 6 & 7 & 6 \end{bmatrix}$$

In the same manner, a matrix of intervals was formed from the model /ɻ/ - POH.

$$M= \begin{bmatrix} 4 & 4 & 4 & 4 & 9 & 8 & 7 & 5 \\ 4 & 4 & 4 & 4 & 9 & 8 & 7 & 5 \\ 4 & 4 & 4 & 4 & 9 & 8 & 7 & 5 \\ 4 & 4 & 4 & 4 & 9 & 8 & 7 & 5 \\ 4 & 4 & 9 & & 8 & 9 & & \end{bmatrix}$$

An average pitch period sequence was constructed from each of these matrices. This is the step in this technique that produces the unsatisfactory results. The problem is that there is more than one average pitch period sequence. For instance, the array Na can be partitioned as follows.

$$\left[\begin{array}{cc|c|cc|cc|c|c|c} & & & & & & & & & 5 \\ 4 & 4 & 5 & 4 & 4 & 6 & 7 & 6 & & 5 \\ 4 & 5 & 8 & & 3 & 7 & 7 & 5 & & 6 \\ 3 & 4 & 4 & 5 & 4 & 6 & 7 & 5 & & 7 \\ 3 & 4 & 4 & 5 & 3 & 7 & 6 & 7 & & 5 \\ 3 & 5 & 4 & 4 & 4 & 6 & 7 & 6 & & \end{array}\right]$$

This produces an average pitch period sequence

$$N_a^1 = (7.8,\ 8.6,\ 10.0,\ 6.8,\ 5.8,\ 5.6)$$

If the other two matrices are partitioned in the same manner, the average pitch period sequences are:

For Ns: $N_s^1 = (9.0,\ 8.2,\ 8.4,\ 6.4,\ 6.8,\ 5.8)$

For M: $M^1 = (8.0,\ 8.2,\ 8.8,\ 8.2,\ 7.0,\ 5.0)$

Other partitions are possible, however. For instance, consider:

$$\left[\begin{array}{cc|c|cc|cc|c|c|c} & & & & & & & & & 5 \\ 4 & 4 & 5 & 4 & 4 & 6 & 7 & 6 & & 5 \\ 4 & 5 & 8 & & 3 & 7 & 7 & 5 & & 6 \\ 3 & 4 & 4 & 5 & 4 & 6 & 7 & 5 & & 7 \\ 3 & 4 & 4 & 5 & 3 & 7 & 6 & 7 & & 5 \\ 3 & 5 & 4 & 4 & 4 & 6 & 7 & 6 & & \end{array}\right]$$

In this case,

For Na: $N_a^2 = (7.8,\ 8.6,\ 16.8,\ 5.8,\ 5.6)$

For Ns: $N_s^2 = (9.0,\ 8.2,\ 14.8,\ 6.8,\ 5.8)$

For M: $M^2 = (8.0,\ 8.2,\ 17.0,\ 7.0,\ 5.0)$

The next step in the proposed quantitative technique was to compute an error function that compared the model average pitch period sequence to those of the candidate alignments. The error metric used was $e=\Sigma|m_i-n_i|$. Using the first partition, $e_a=5.0$ and $e_s=4.2$; using the second partition, $e_a=2.6$ and $e_s=4.2$. Therefore, the conclusion depends on the partition.

The possibility of using standard correlation techniques to compare candidate alignments was also investigated. These were rejected because there was insufficient correlation between the height or area of a single peak in a POH and the magnitude of the corresponding peak in the stimulus.

It was, therefore, necessary to use visual correlation to compare the candidate alignments of the neuron/model vowel-POH pairs. Each pair was compared at each candidate alignment, and if there was a clearly superior alignment, or a clearly poor one, it was noted. These conclusions were compared with those of the previous step, and any discrepancies resolved (There were very few). For example, comparing the model and neuron /ṛ/ - POHs, it was concluded that the histogram pair associated with stimulus 7A had a better correlation using the "right shift (3)" alignment. Similarly, the pair associated with stimulus 8A had a better correlation as aligned.

The fourth step in the alignment procedure was to use all existing information generated to this point to propose the most probable alignments for each neuron/model pair. For example, based on the weight of evidence, the conclusion on the alignment of the /ṛ/-POH pairs was:

3B left shift (5)
4B as aligned
7A right shift (3)
8A as aligned

The fifth step was to compare these proposed alignments across each stimulus, to check for any contradictions.

The final step was to assign the alignments of those pairs where a decision could not be made. This assignment was made on the basis of the other assigned alignments in the stimulus. For example, the alignment of the /ɔ/ segment in stimulus 7A could not be assigned on the basis of the information generated at any previous step. The alignment of the other vowels in this stimulus were determined, however, and the only neuron/model /ɔ/ -POH alignment consistent with these is the one shown in Figure 21.

3.3 THE VOWEL /ɹ̣/

As illustrated in Figure 6, the neuron /ɹ̣/ - POH from the 10 and 20dB attenuation experiments have peaks corresponding in time to each of the nine peaks in the vowel's pitch period, just as the model does. The corresponding /ɹ̣/ -PIHs (Figure 8) reflect this, since, as Table 5 demonstrates, there is little difference in the position of the peaks in the neuron and model histograms.

Figure 7 reveals that the model /ɹ̣/-POH from the 40 dB attenuation experiment has lost the peaks corresponding to pitch period peaks 2 and 4. These peaks remain in the neuron/ɹ̣/-POH generated at that intensity. This observation is supported in the corresponding 40 dB /ɹ̣/-PIH of Figure 9. As Table 5 demonstrates, there is a strong peak in the neuron /ɹ̣/-PIH at the interval of 1.2 msec, which is the interval between each of the pitch period peaks 1, 2, 3, and 4. This peak is missing from the model 40 dB /ɹ̣/-PIH.

3.4 THE VOWEL /ə/

The /ə/ -POHs from the neuron and the model are juxtaposed with their corresponding ROC COC2 responses in Figures 10 and 11.

A pitch period of the ROC COC2 response is superimposed on a typical corresponding segment of the neuron's 20 dB /ə/ -POH in Figure 12 (a) and on a typical corresponding segment of the model's 20 dB /ə/ -POH in Figure 12(b). There are three neuron /ə/ -POH peaks that do not correspond to the leading edge of ROC COC2 response peaks 2, 3, and 4. The addition of these peaks makes the histogram very regular in time, with a period of about 1 msec.

It is interesting to note that this period does not correspond to a peak in the /ə/ -PIH (Figure 14 and Table 7). Instead, there are peaks in the /ə/-PIH at 1.8, 2.8, and 3.6 msec, indicating that, after firing once, the neuron skips over the next opportunity to fire. This makes the neuron's /ə/ -PIH look more like the model's /ə/-PIH than the neuron's /ə/-POH would suggest.

Text continued on page 44

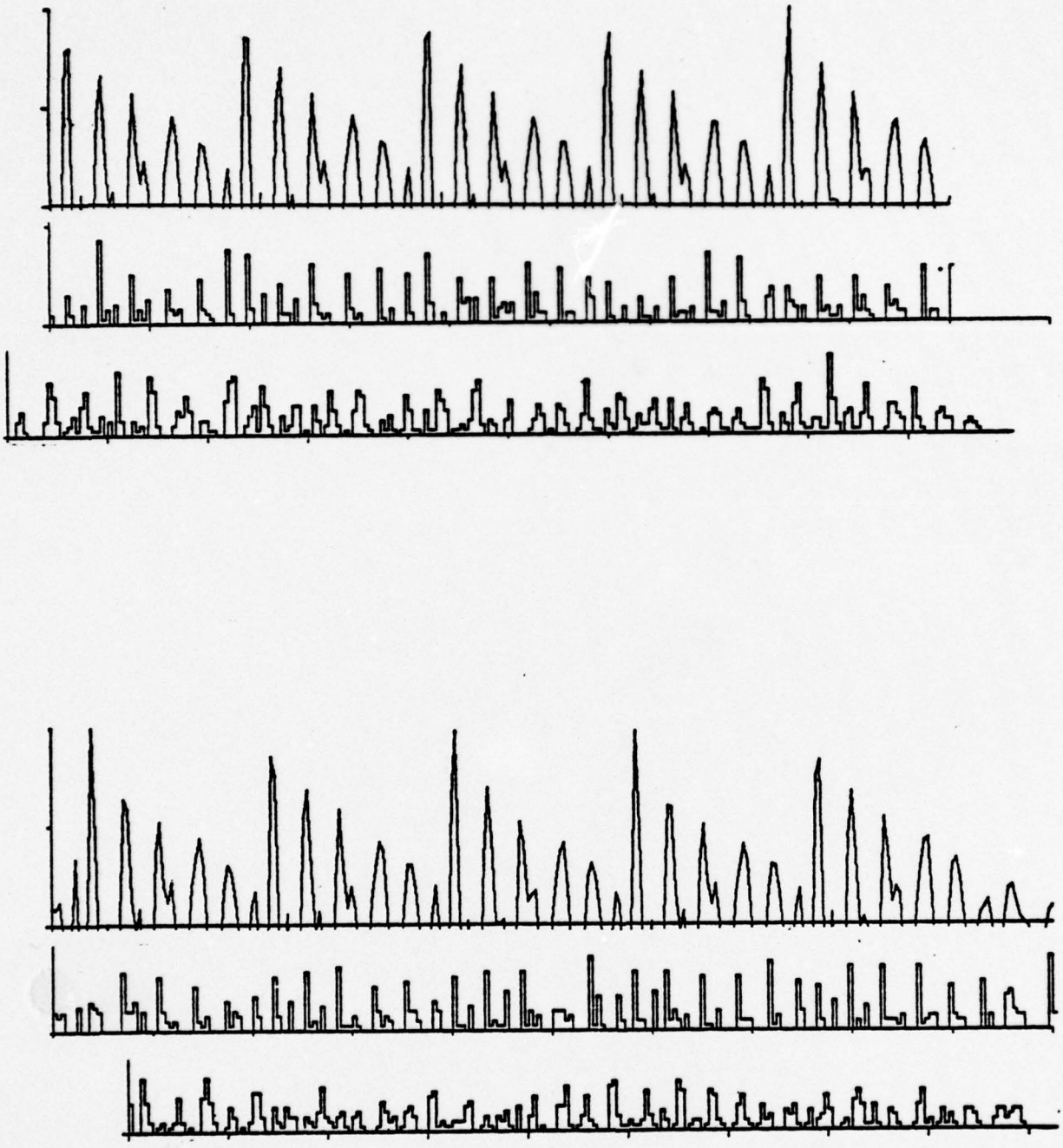


Figure 4. /ɹ/-POHs from neuron 710827/11, (lower curve) in (a) and (b)) and Model 08/13/76, (middle curve in (a) and (b)) and corresponding segment from the ROC COC2 response, positive values only (upper curve in (a) and (b)). In (a) the neuron run is 7, the model run is 08/13/76.1/2, and the stimulus is 3B, presented at an intensity of 10 dB attenuation. In (b) the neuron run is 14, the model run is 08/13/76.2/1, and the stimulus is 7A, presented at an intensity of 10 dB attenuation.

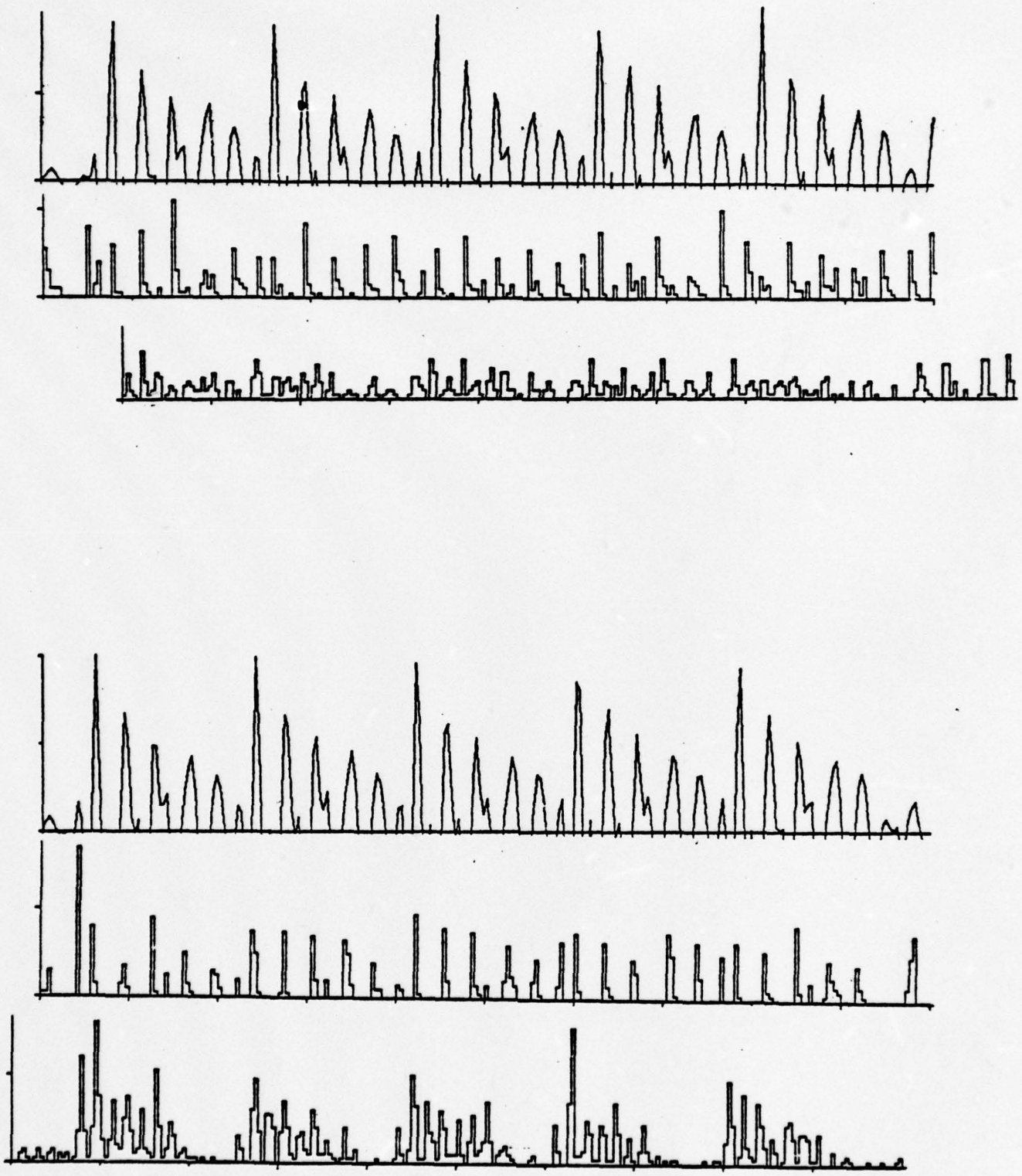


Figure 5. /ṛ/-POHs from neuron 710827/11 (lower curve in (a) and (b)) and Model 08/13/76 (middle curve in (a) and (b)) and corresponding segment from the ROC COC2 response, positive values only (upper curve in (a) and (b)). In (a) the neuron run is 16, the model run is 08/13/76.2/3, and the stimulus is 8A, presented at an intensity of 20 dB attenuation. In (b) the neuron run is 9, the model run is 08/13/76.1/4, and the stimulus is 4B, presented at an intensity of 40 dB attenuation.

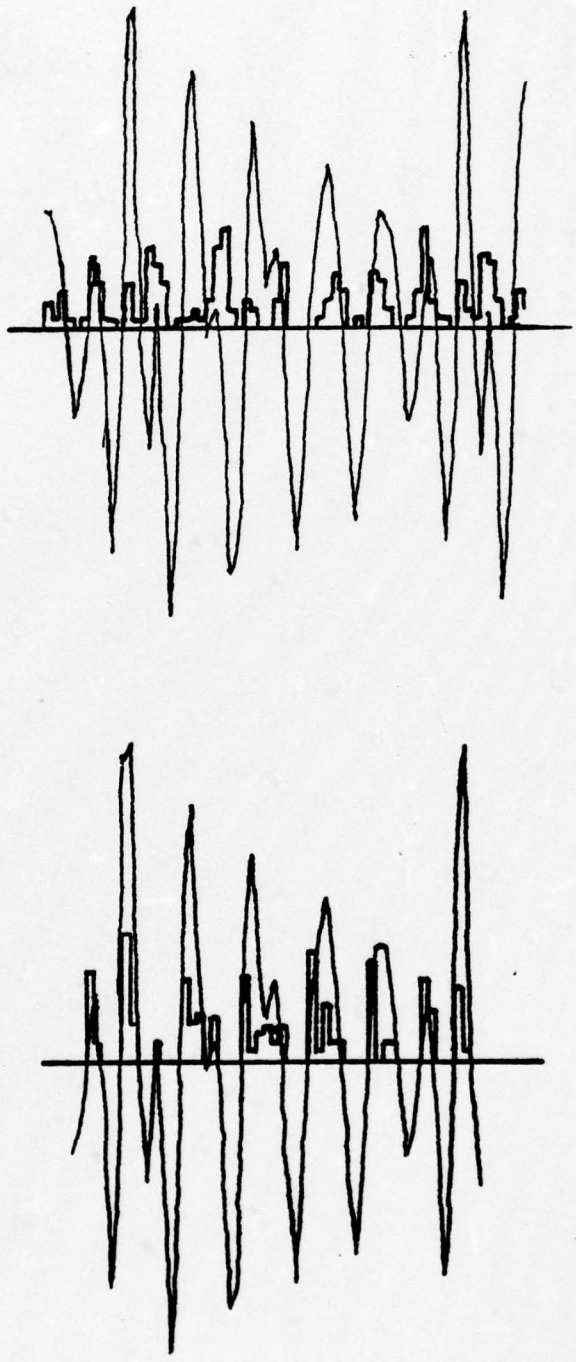


Figure 6. A pitch period of the vowel /ɹ̥/ superimposed on a typical corresponding segment of a 10 dB attenuation, /ɹ̥/-POH. (a) is neuron 710827, run 7. (b) is model run 08/13/76.1/2.

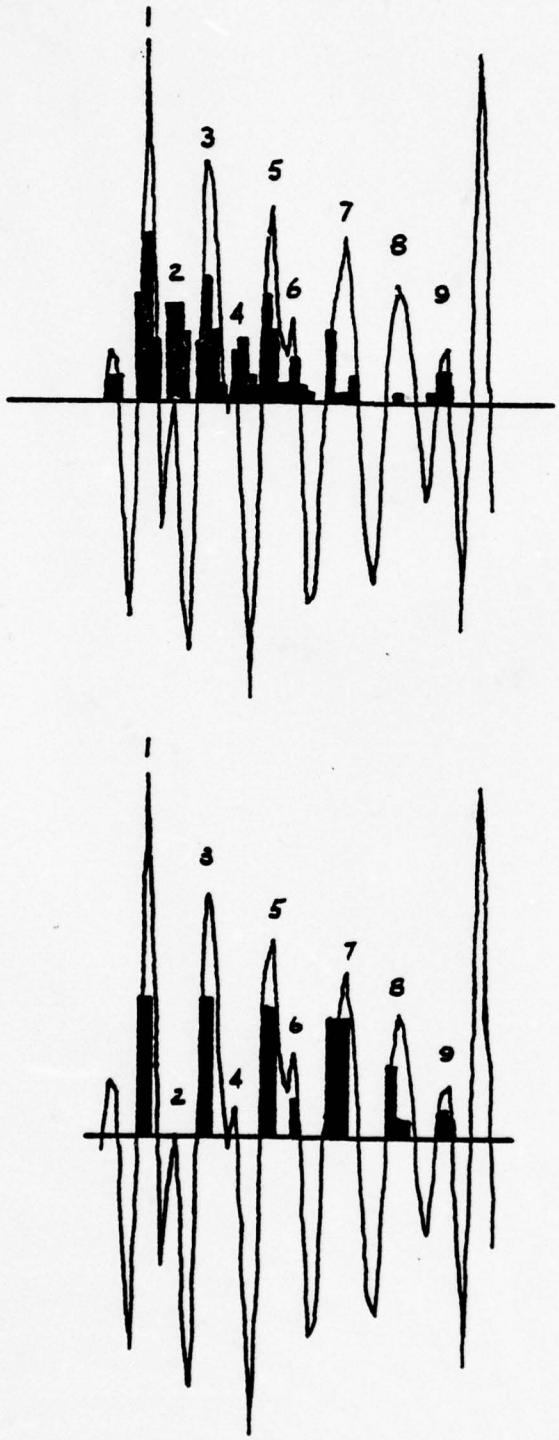


Figure 7. A pitch period of the vowel /ɹ̥/ superimposed on a typical corresponding segment of a 40 dB attenuation /ɹ̥/-POH. (a) is neuron 710827, run 9. (b) is model run 08/13/76.1/4.

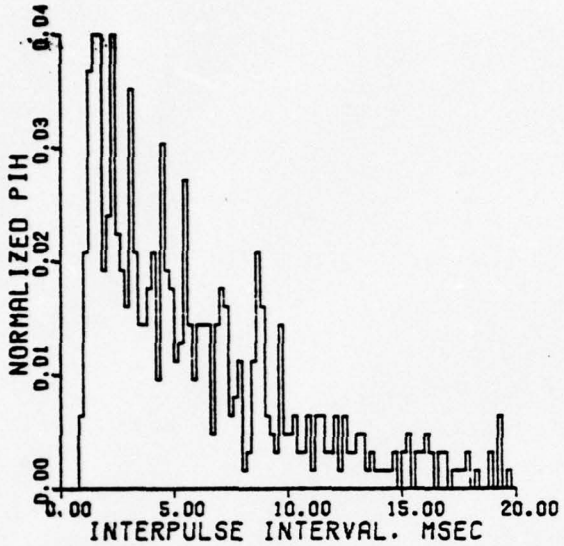


FIGURE 710827 . 11.. 7.
DEFINING INTERVALS 234 TO 459
AVERAGE = 6.07 NUMBER OF INTERVALS = 572

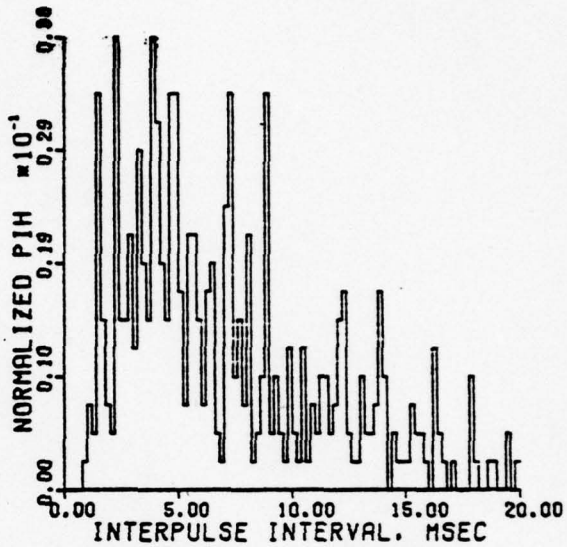


FIGURE LEET. 0 . 08/13/76.1. 2.
DEFINING INTERVALS 226 TO 450
AVERAGE = 7.72 NUMBER OF INTERVALS = 417

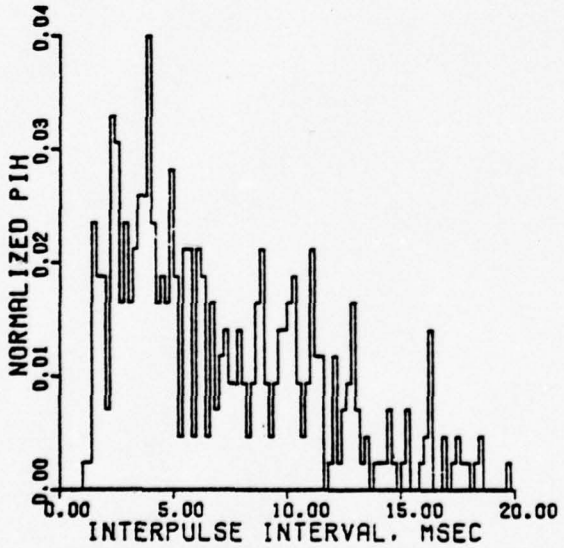


FIGURE 710827 . 11.. 14.
DEFINING INTERVALS 459 TO 672
AVERAGE = 7.34 NUMBER OF INTERVALS = 414

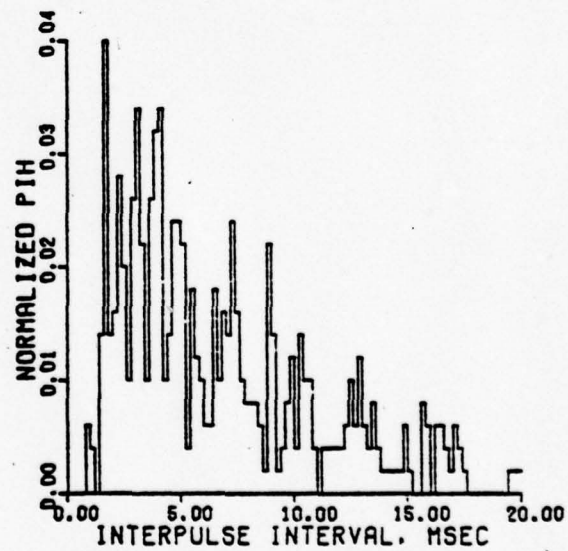
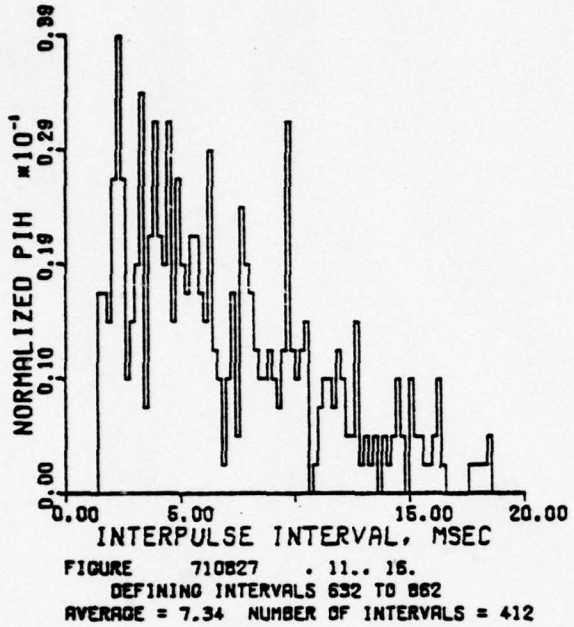
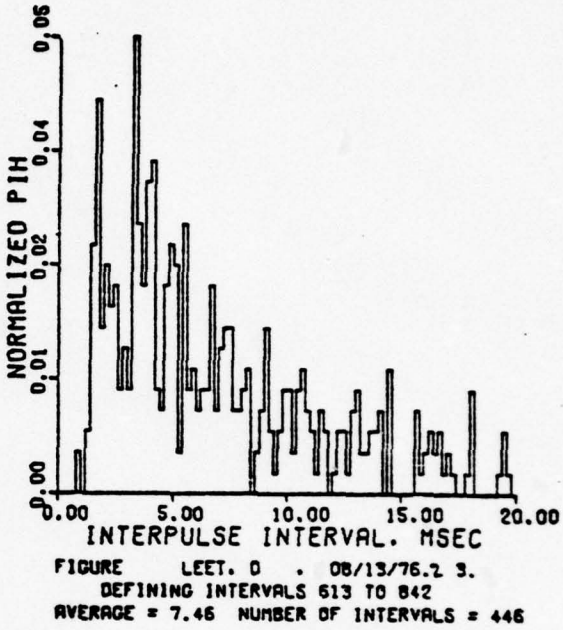
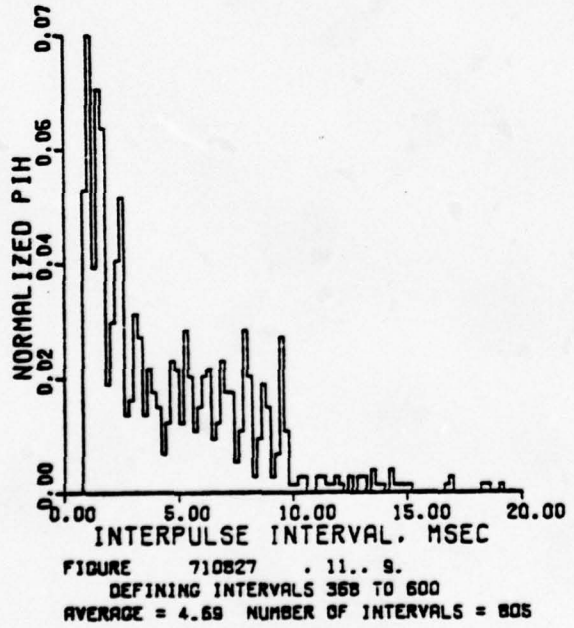


FIGURE LEET. 0 . 08/13/76.2 1.
DEFINING INTERVALS 428 TO 657
AVERAGE = 7.37 NUMBER OF INTERVALS = 453

Figure 8. /ṛ/-PIHs of neuron 710827/11 and Model 08/13/76 corresponding to the /ṛ/-POHs of Figure 4. (a) neuron run 7, (b) Model run 08/13/76.1/2, (c) neuron run 14, and (d) Model run 08/13/76.2/1.







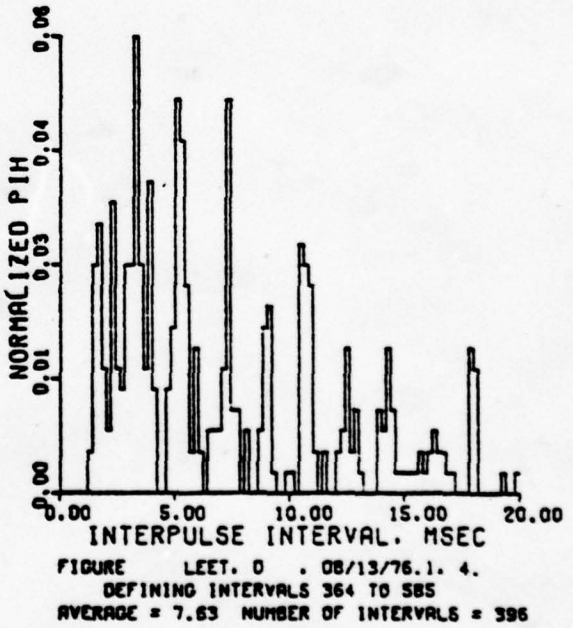


Figure 9. /ɾ/-PIHs of neuron 710827/11 and Model 08/13/76 corresponding to the /ɾ/-POHs of Figure 5. (a) neuron run 16, (b) Model run 08/13/76.2/3, (c) neuron run 9, and (d) Model run 08/13/76.1/4.

TABLE 5

PEAK OCCURRENCE TABLE - VOWEL /ɹ/

Interpulse Interval	710827/11 Run 7	08/13/76.1 Run 2	710827/11 Run 14	08/13/76.2 Run 1	710827/11 Run 16	08/13/76.2 Run 3	710827/11 Run 9	08/13/76.1 Run 4
1.0				.011		.004		
1.2		.014					.158	
1.4								
1.6	.159	.053	.046				.159	
1.8				.075	.049	.087		.076
2.0								
2.2						.063		
2.4	.118	.058	.072	.071	.092			.058
2.6						.054	.097	
2.8								
3.0		.048	.058			.038		
3.2	.098			.091			.068	
3.4		.060			.061	.090		.111
3.6								
3.8							.048	
4.0		.084	.092		.075			.066
4.2	.052			.084		.081		
4.4								
4.6	.081		.053		.066			
4.8		.082					.052	
5.0			.065	.077	.061	.074		
5.2								.111
5.4							.056	
5.6	.059		.048	.038	.061	.045		
5.8		.058						
6.0						.034		.028
6.2								
6.4	.047				.056		.047	
6.6		.041		.038				
6.8			.029			.043		
7.0				.044			.045	

No. Sample Intervals	226	225	214	230	231	230	233	222
Average	6.07	7.72	7.34	7.37	7.34	7.46	4.69	7.63
Number Intervals	572	417	414	453	412	446	805	396
Vowel Location	3B(2)	3B(2)	7A(3)	7A(3)	8A(4)	8A(4)	4B(3)	4B(3)
Intensity	10	10	10	10	20	20	40	40

TABLE 6

STIMULUS INTERVALS TABLE
VOWEL /ɹ/

INTERVAL	STIMULUS			
	3B	7A	8A	4B
.2	0	0	0	0
.4	0	0	0	0
.6	0	3	0	1
.8	16	13	14	7
1.0	4	7	4	4
1.2	0	0	0	2
1.4	5	4	4	4
1.6	17	18	14	13
1.8	10	12	12	6
2.0	0	0	0	2
2.2	0	2	1	0
2.4	11	10	7	7
2.6	8	10	10	5
2.8	0	0	0	1
3.0	4	3	2	5
3.2	9	9	7	7
3.4	13	14	16	11
3.6	0	2	1	0
3.8	0	1	0	0
4.0	8	8	7	8
4.2	11	12	11	6
4.4	1	1	1	3
4.6	0	0	0	3
4.8	11	10	7	4
5.0	9	7	9	10
5.2	1	5	5	1
5.4	0	0	0	0
5.6	8	8	5	7
5.8	9	9	10	10
6.0	3	2	4	3
6.2	0	0	0	1
6.4	4	1	1	6
6.6	9	11	10	6
6.8	1	1	3	1
7.0	0	0	0	1
7.2	1	0	0	4
7.4	2	2	4	3
7.6	0	0	1	1
7.8	0	0	0	0
8.0	0	0	0	0

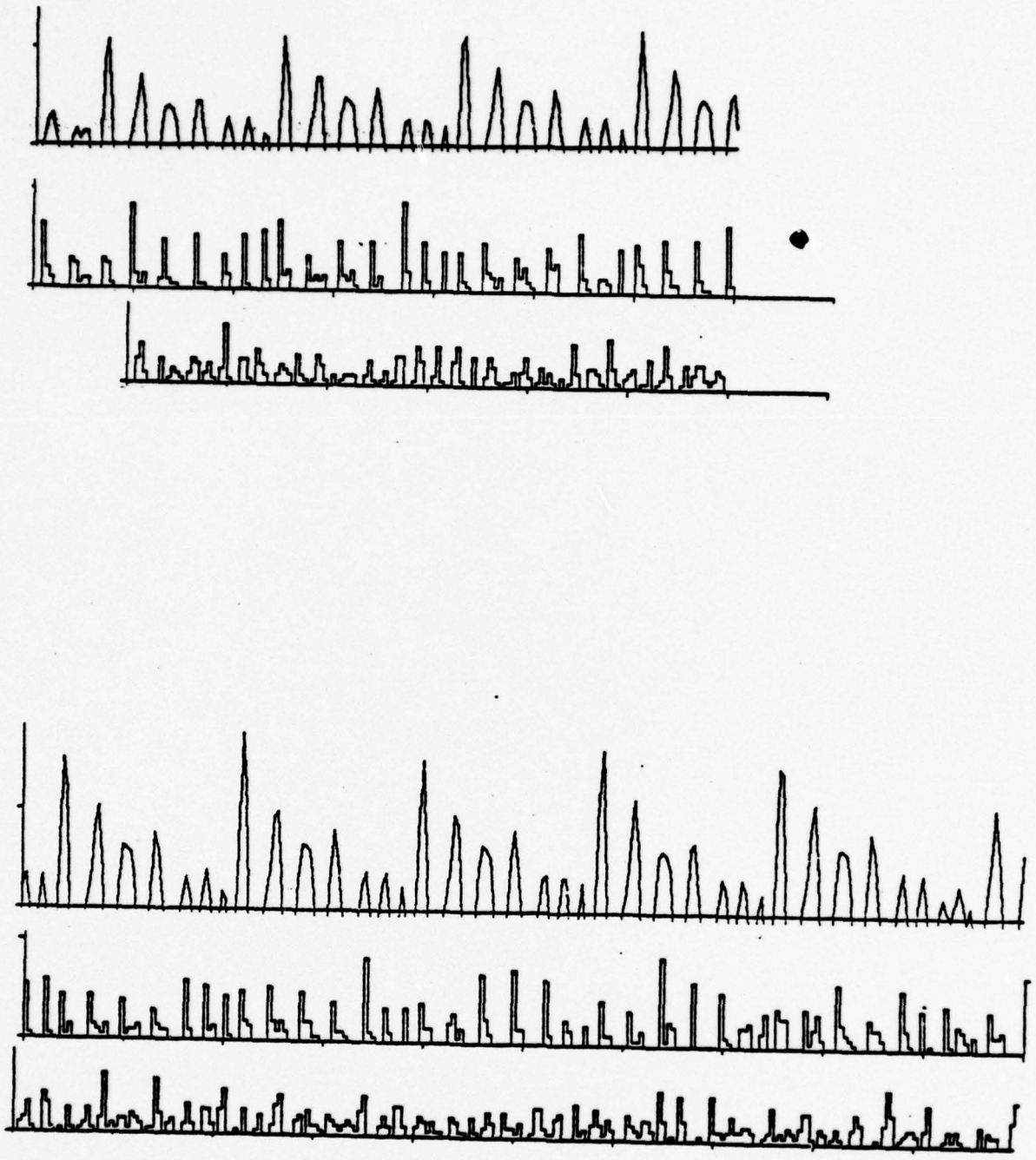


Figure 10. /ə/-POHs from neuron 710827/11 (lower curve in (a) and (b)) and Model 08/13/76 (middle curve in (a) and (b)) and corresponding segment from the ROC COC2 response, positive values only (upper curve in (a) and (b)). In (a) the neuron run is 7, the model run is 08/13/76.1/2, and the stimulus is 3B, presented at an intensity of 10 dB attenuation. In (b) the neuron run is 15, the model run is 08/13/76.2/2, and the stimulus is 7B, presented at an intensity of 10 dB attenuation.

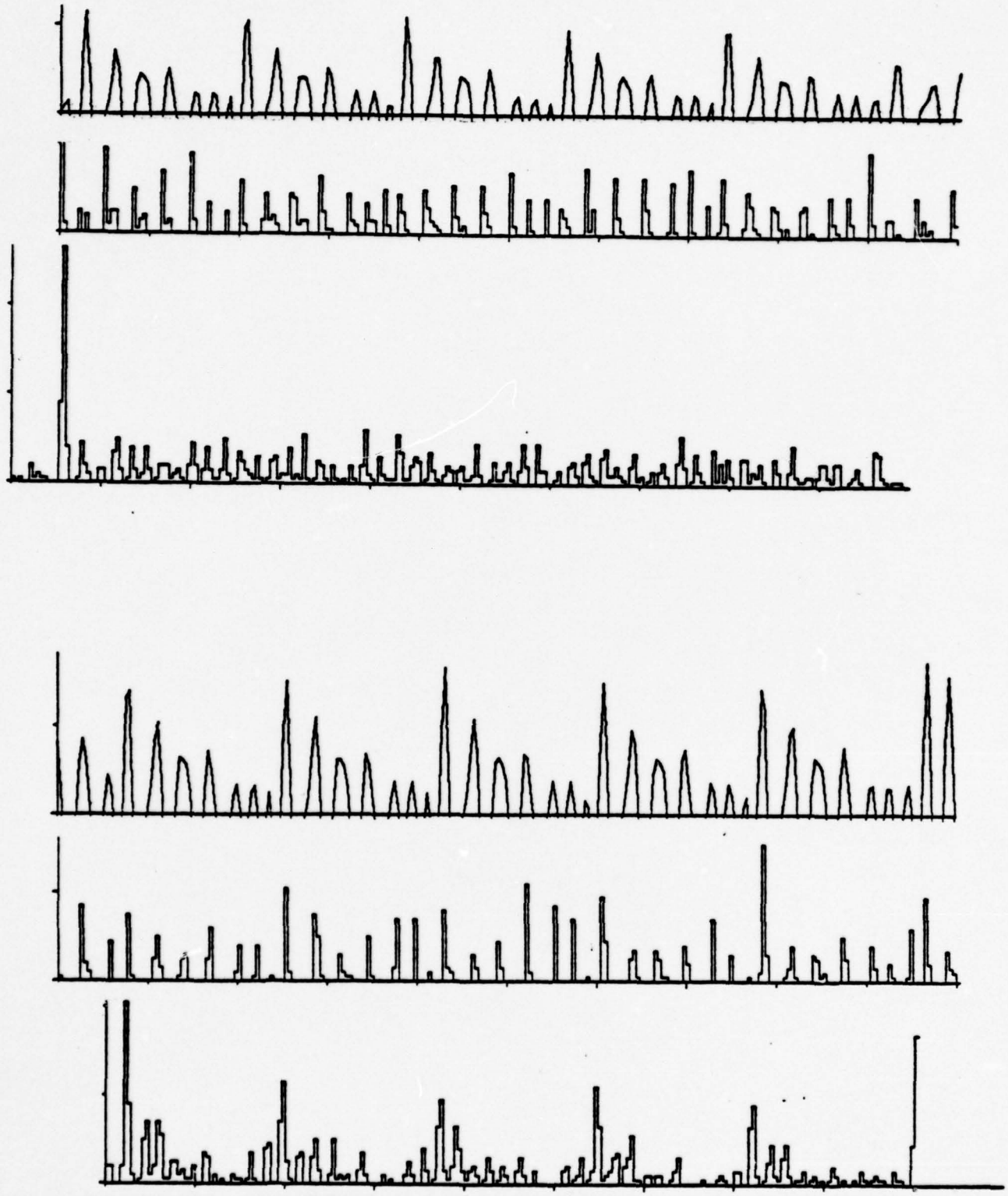


Figure 11. /ə/-POHs from neuron 710827/11 (lower curve in (a) and (b)) and Model 08/13/76 (middle curve in (a) and (b)) and corresponding segment from the ROC COC2 response, positive values only (upper curve in (a) and (b)). In (a) the neuron run is 16, the model run is 08/13/76.2/3, and the stimulus is 8A, presented at an intensity of 20 dB attenuation. In (b) the neuron run is 8, the Model run is 08/13/76.1/3, and the stimulus is 4A, presented at an intensity of 40 dB attenuation.

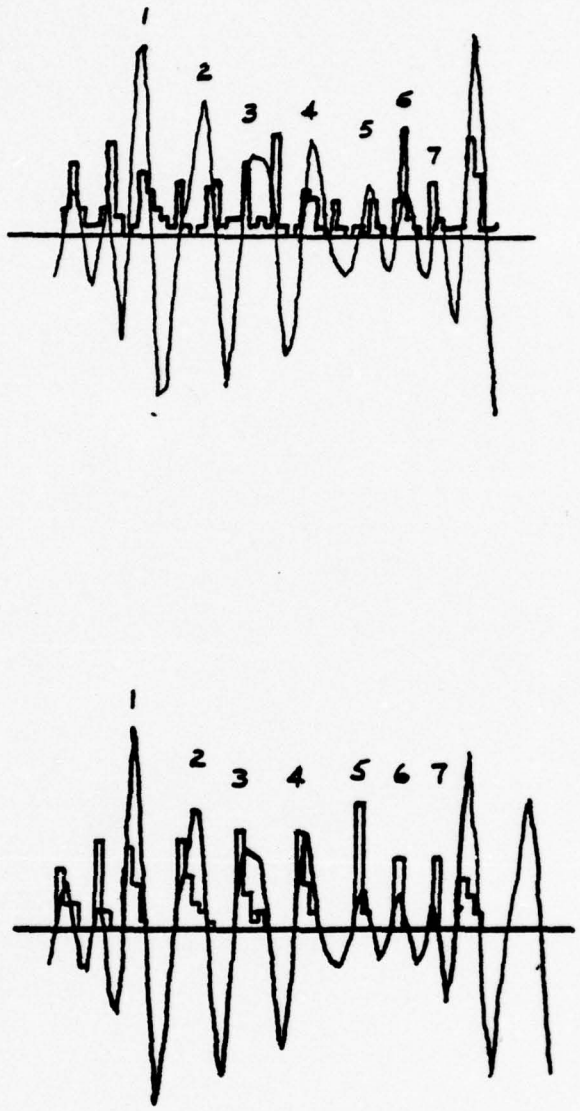
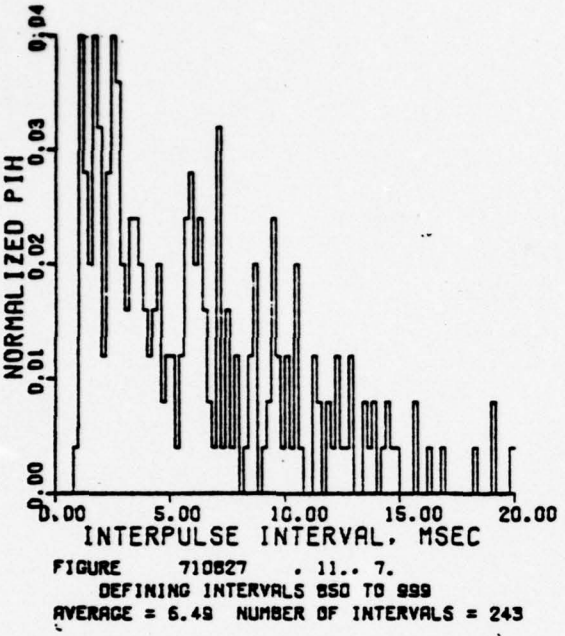
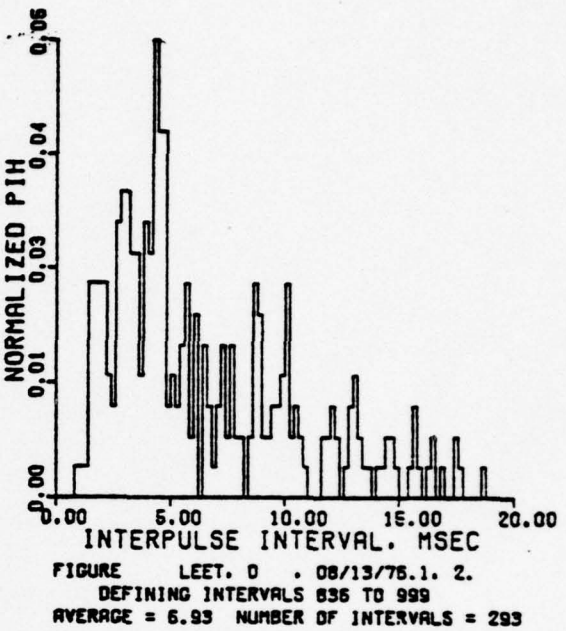
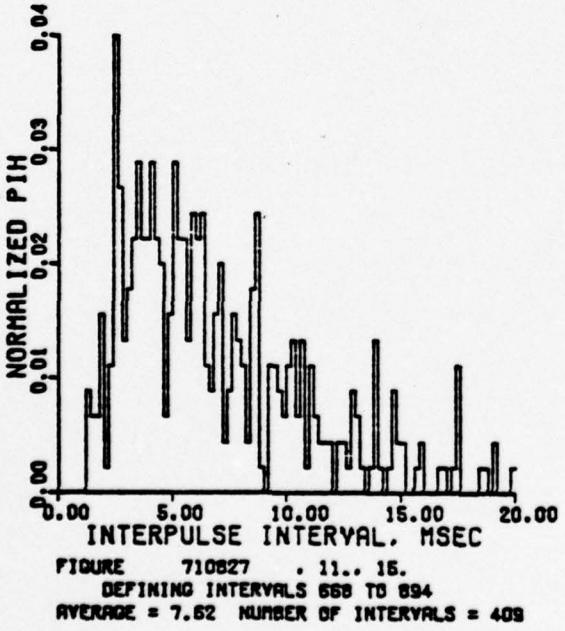


Figure 12. A pitch period of the vowel /ə/ superimposed on a typical corresponding segment of the 20 dB attenuation /ə/-POH. (a) is neuron 710827, run 16. (b) is model run 08/13/76.2/3.







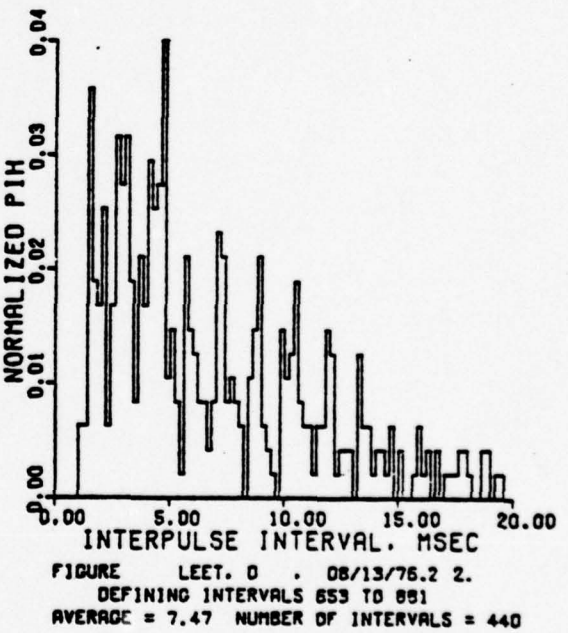
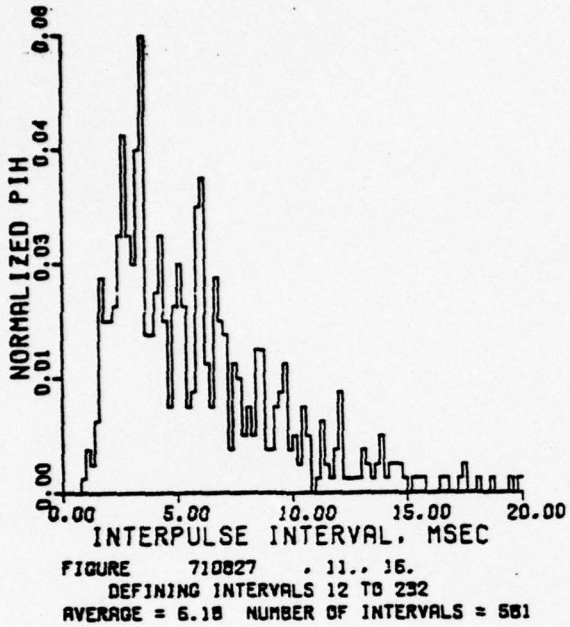
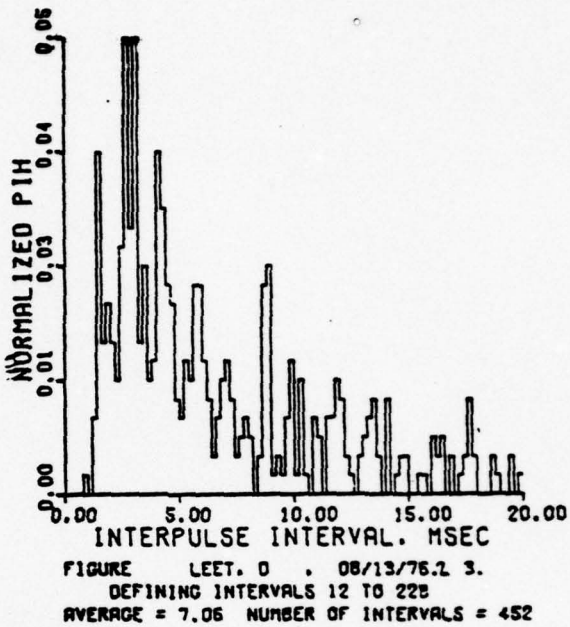
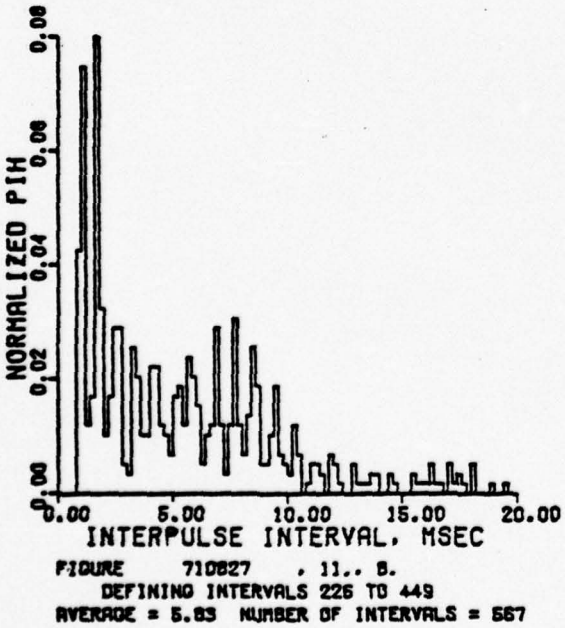


Figure 13. /ə/-PIHs of neuron 710827/11 and model 08/13/76 corresponding to the /ə/-POHs of Figure . (a) neuron run 7, (b) model run 08/13/76.1/2, (c) neuron run 15, and (d) model run 08/13/76.2/2.







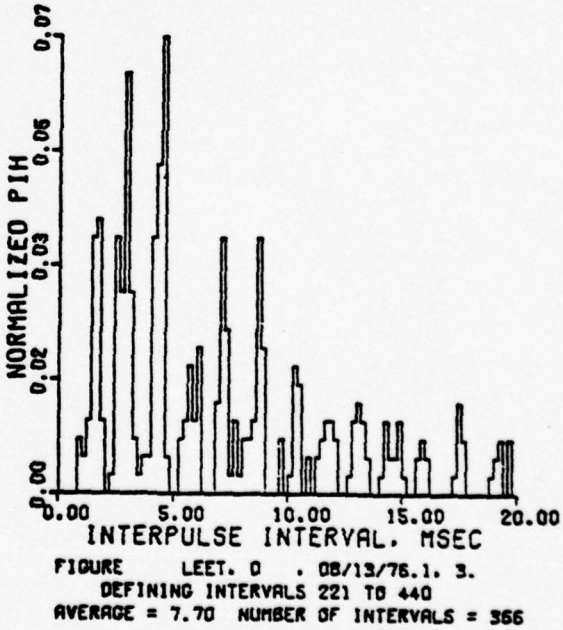


Figure 14. /ə/-PIHs of neuron 710827/11 and model 08/13/76 corresponding to the /ə/-POHs of Figure . (a) neuron run 16, (b) model run 08/13/76.2/3, (c) neuron run 8, and (d) model run 08/13/76.1/3.

3.5 THE VOWEL /a/

The alignments of the neuron /a/-POHs with their corresponding model /a/-POHs and ROC COC2 response segments are shown in Figures 15 and 16.

In Figure 17 a pitch period of the ROC COC2 response is superimposed on typical corresponding segments of the neuron and model 20 dB attenuation /a/-POHs. Notice that in some cases there are two peaks in the neuron /a/-POH corresponding to ROC COC2 response peak 3. Another observation is that there is consistently more activity in the neuron /a/-POHs associated with peak 8 than in the corresponding model histogram. As a matter of fact, in the model's 40 dB /a/-POH, activity associated with peak 8 ceases altogether.

Overall, the correlation between the neuron and model /a/-POHs is good. As would be expected, the location of the peaks in the /a/-PIHs also compare favorably (Figures 18 and 19 and Table 9).

3.6 THE VOWEL /ɔ/

The neuron /ɔ/-POHs are aligned with their corresponding model /ɔ/-POHs and ROC COC2 response segments in Figures 20 and 21.

A pitch period of the ROC COC2 response has been superimposed on typical corresponding segments of neuron and model /ɔ/-POHs in Figure 22. The correlation of the neuron /ɔ/-POH with both the Model /ɔ/-POH segment and the ROC COC2 response is good.

It is remarkable that with this good correlation the neuron and model 10 dB /ɔ/-PIHs are as different as they are (Figures 23 and 24 and Table 11).

The observations that the neuron /ɔ/-PIHs have prominent peaks at short intervals and that the model /ɔ/-PIHs have prominent peaks at longer intervals (3.0, 5.4-5.6, and 6.6 msec) suggest that the neuron has a greater tendency than the model of firing on adjacent peaks in the pitch period.

An observation can be made on the 40 dB run: the activity of the model is much greater than the activity of the neuron (355 intervals to 133 intervals).

Text continued on page 61

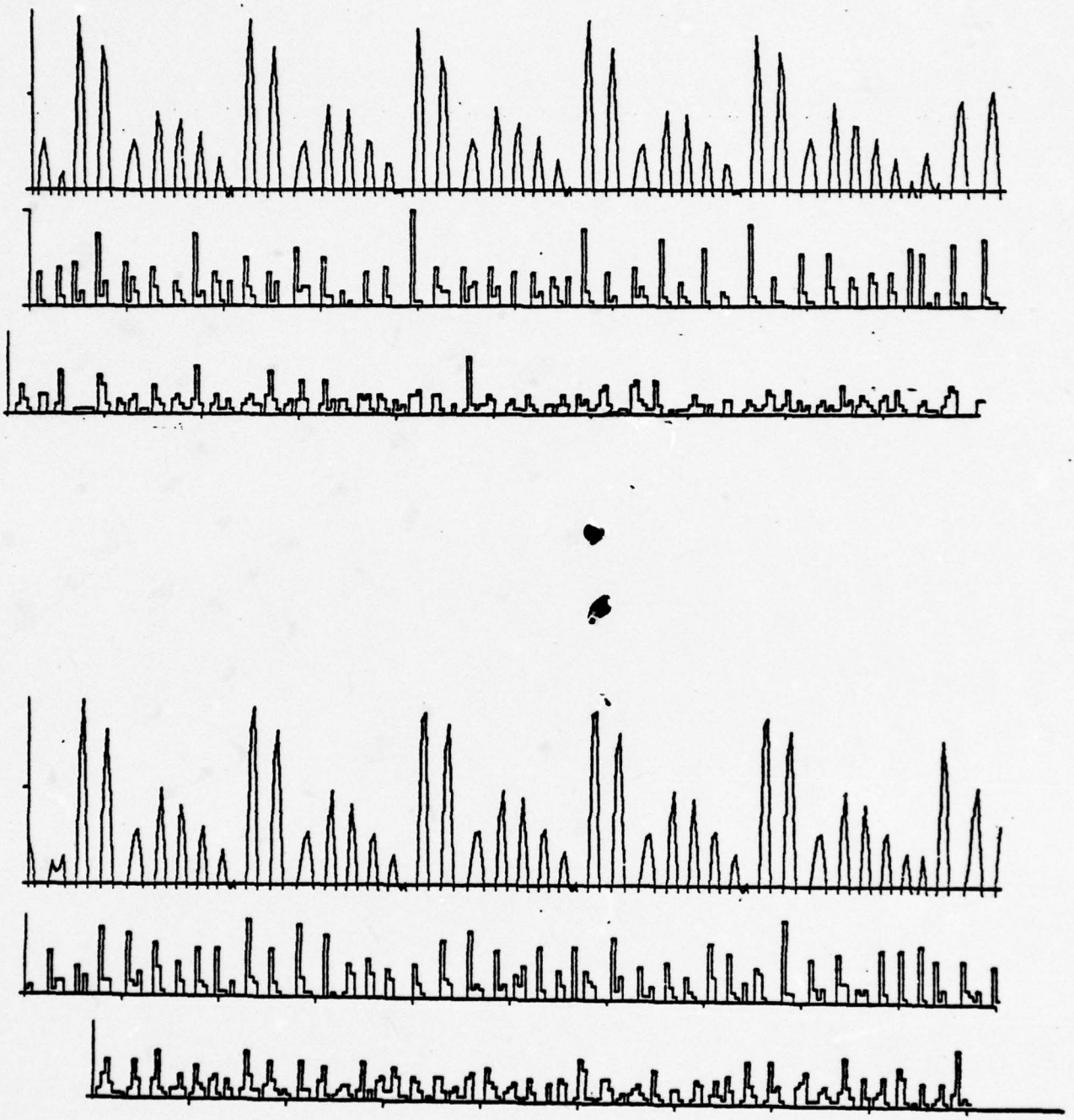


Figure 15. /a/-POHs from neuron 710827/11 (lower curve in (a) and (b)) and model 08/13/76 (middle curve in (a) and (b)) and corresponding segment from the ROC COC2 response, positive values only (upper curve in (a) and (b)). In (a) the neuron run is 6, the model run is 08/13/76.1/1, and the stimulus is 3A, presented at an intensity of 10 dB attenuation. In (b) the neuron run is 15, the model run is 08/13/76.2/2, and the stimulus is 7B, presented at an intensity of 10 dB attenuation.

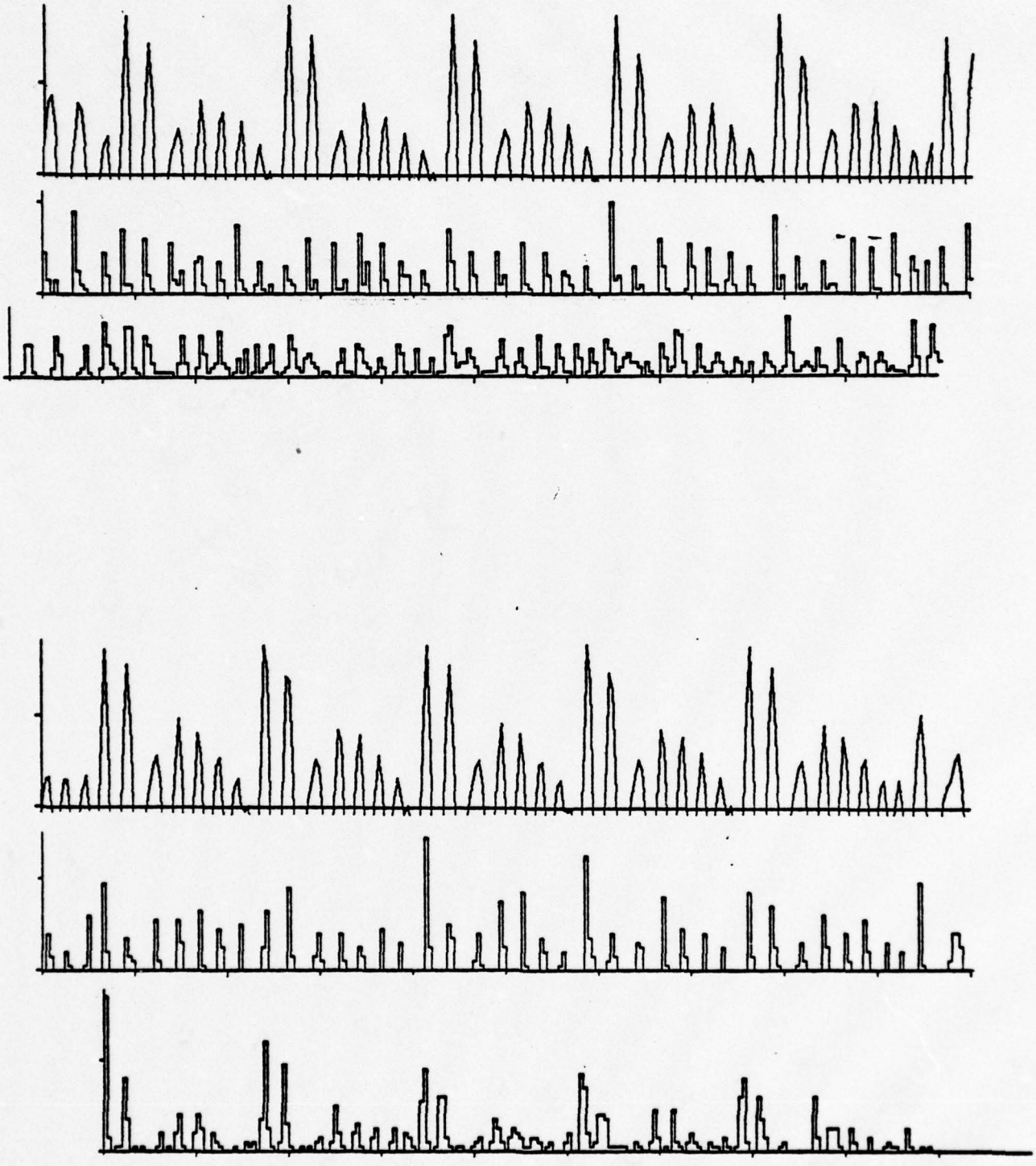


Figure 16. /a/-POHs from neuron 710827/11 (lower curve in (a) and (b)) and model 08/13/76 (middle curve in (a) and (b)) and corresponding segment from the ROC COC2 response, positive values only (upper curve in (a) and (b)). In (a) the neuron run is 17, the model run is 08/13/76.2/4, and the stimulus is 8B, presented at an intensity of 20 dB attenuation. In (b) the neuron run is 8, the model run is 08/13/76.1/3, and the stimulus is 4A, presented at an intensity of 40 dB attenuation.

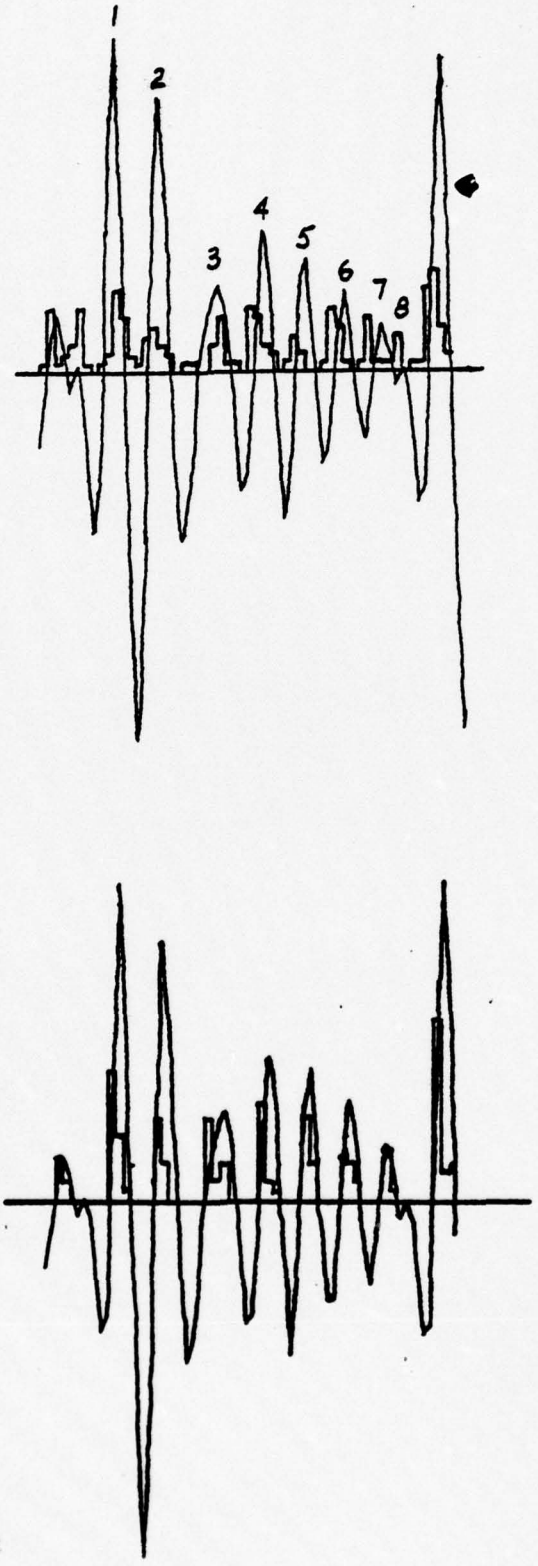


Figure 17. A pitch period of the vowel /a/ superimposed on a typical corresponding segment of the 20 dB /a/-POH. (a) is neuron 710827, Run 17. (b) is Model run 08/13/76.2/4.

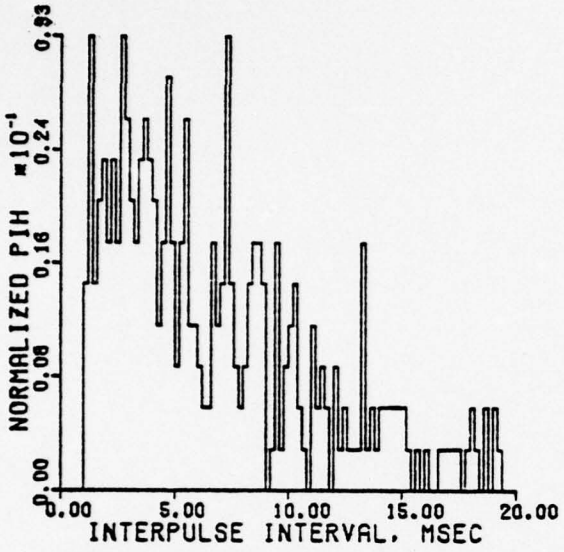


FIGURE 710827 . 11.. 6.
DEFINING INTERVALS 619 TO 640
AVERAGE = 7.61 NUMBER OF INTERVALS = 338

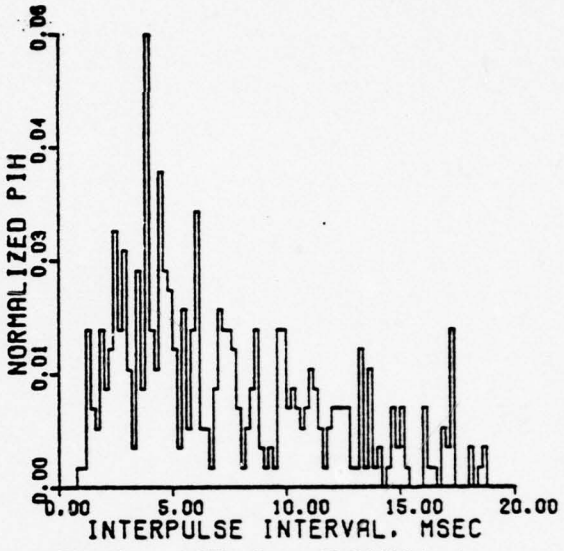


FIGURE LEET. 0 . 08/13/76.1. 1.
DEFINING INTERVALS 611 TO 832
AVERAGE = 7.68 NUMBER OF INTERVALS = 415

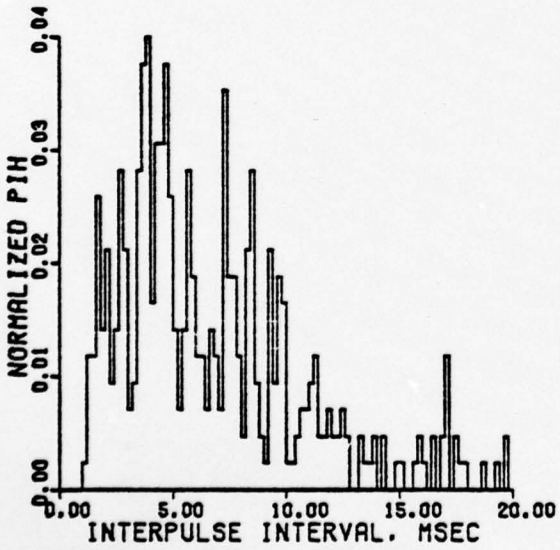


FIGURE 710827 . 11.. 15.
DEFINING INTERVALS 450 TO 667
AVERAGE = 7.45 NUMBER OF INTERVALS = 419

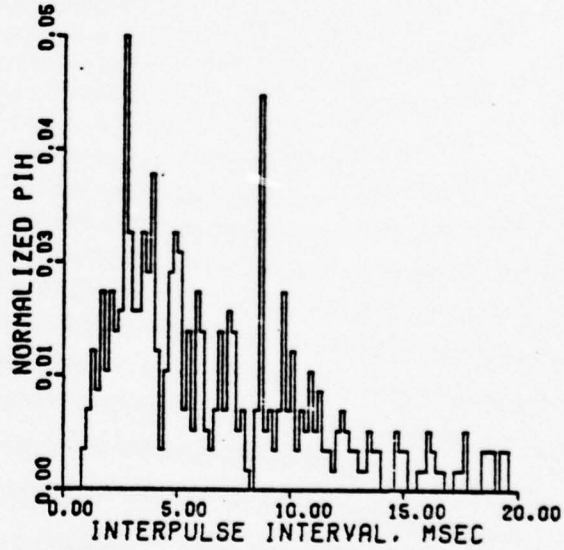
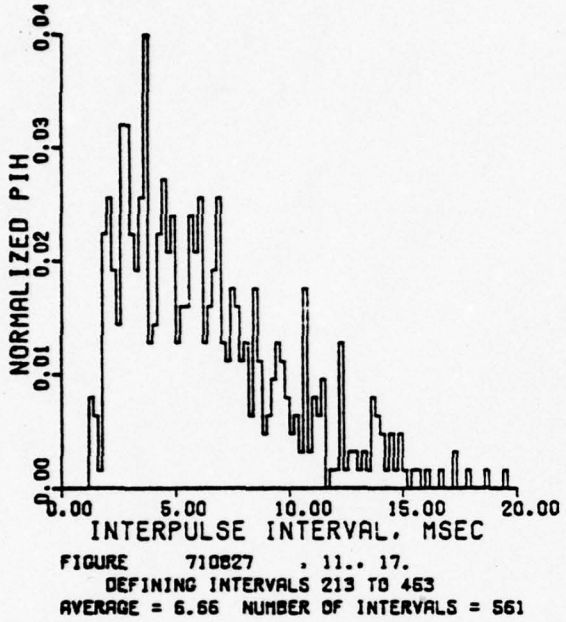
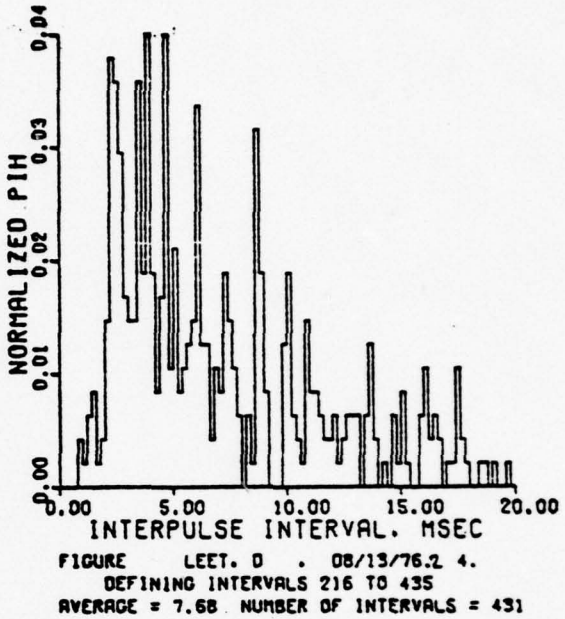
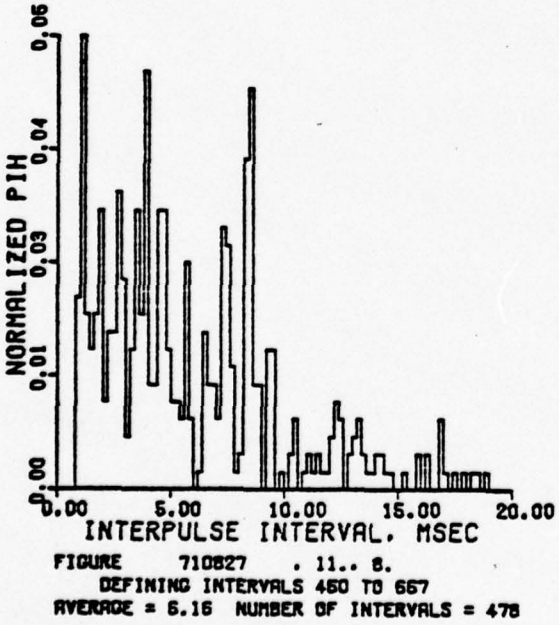


FIGURE LEET. 0 . 08/13/76.2 2.
DEFINING INTERVALS 433 TO 652
AVERAGE = 7.33 NUMBER OF INTERVALS = 440

Figure 18. /a/-PIHs of neuron 710827/11 and Model 08/13/76 corresponding to the /a/-POHs of Figure . (a) neuron run 6, (b) model run 08/13/76.1/1, (c) neuron run 15, and (d) model run 08/13/76.2/2.







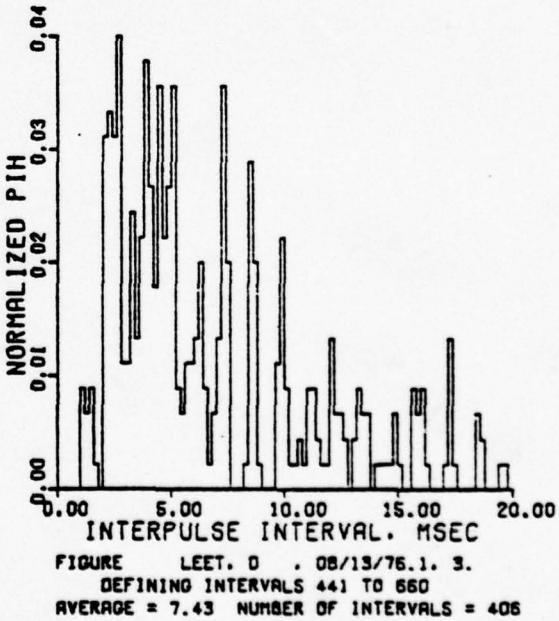


Figure 19. /a/-PIHs of neuron 710827/11 and Model 08/13/76 corresponding to the /a/-POHs of Figure . (a) neuron run 17, (b) model run 08/13/76.2/4, (c) neuron run 8, and (d) model run 08/13/76.1/3.

TABLE 7

PEAK OCCURRENCE TABLE - VOWEL /ə/

Interpulse Interval	710827/11 Run 7	08/13/76.1 Run 2	710827/11 Run 15	08/13/76.2 Run 2	710827/11 Run 16	08/13/76.2 Run 3	710827/11 Run 8	08/13/76.1 Run 3
1.0						.002		.014
1.2	.074				.017		.134	
1.4			.017					
1.6				.066		.066		
1.8	.095	.072			.055		.134	.090
2.0			.027			.058		
2.2				.052				
2.4								
2.6	.107		.086					.071
2.8				.082	.105	.113	.065	
3.0		.099						.123
3.2				.084		.102		
3.4							.051	
3.6	.070		.081		.115	.058		
3.8				.050				
4.0		.072						
4.2			.081	.077		.088		
4.4		.119			.076		.058	
4.6	.045							.123
4.8				.084				
5.0	.033							
5.2		.034	.073	.036	.072			
5.4						.038	.049	
5.6								
5.8		.048		.041			.058	.041
6.0	.074		.066			.064		
6.2		.027			.088			.033
6.4	.062		.064					
6.6		.027						
6.8					.057			
7.0						.040	.055	
7.2								.077

No. Sample Intervals	150	164	235	229	221	217	223	220
Average	6.49	6.93	7.62	7.47	6.18	7.06	5.83	7.70
Number Intervals	243	293	409	440	581	452	567	366
Vowel Location	3B(5)	3B(5)	7B(4)	7B(4)	8A(1)	8A(1)	4A(2)	4A(2)
Intensity	10	10	10	10	20	20	40	40

TABLE 8

STIMULUS INTERVALS TABLE
VOWEL /ə/

INTERVAL	STIMULUS			
	3B	7B	8A	4A
.2	0	0	0	0
.4	0	0	0	0
.6	0	0	0	0
.8	3	5	5	1
1.0	6	10	8	1
1.2	1	0	1	3
1.4	5	6	7	1
1.6	8	14	14	9
1.8	4	5	3	1
2.0	4	5	5	0
2.2	2	4	4	2
2.4	1	1	1	0
2.6	2	4	4	0
2.8	5	5	4	2
3.0	3	6	6	2
3.2	9	13	11	4
3.4	1	1	2	4
3.6	3	4	3	0
3.8	2	4	4	2
4.0	1	1	1	0
4.2	6	9	10	1
4.4	3	4	2	5
4.6	5	5	8	2
4.8	4	8	6	0
5.0	0	1	2	3
5.2	4	4	3	0
5.4	2	4	4	2
5.6	4	2	3	4
5.8	5	12	12	1
6.0	5	5	4	3
6.2	2	4	4	0
6.4	2	4	3	0
6.6	1	1	2	2
6.8	3	5	4	1
7.0	3	4	4	0
7.2	1	4	4	7
7.4	0	0	0	2
7.6	0	0	0	3
7.8	0	0	0	0
8.0	0	0	0	2

TABLE 9

PEAK OCCURRENCE TABLE - VOWEL /a/

Interpulse Interval	710827/11 Run 6	08/13/76.1 Run 1	710827/11 Run 15	08/13/76.2 Run 2	710827/11 Run 17	08/13/76.2 Run 4	710827/11 Run 8	08/13/76.1 Run 3
1.0						.007		
1.2	.062						.098	.017
1.4		.031		.036	.016			
1.6						.019		.020
1.8			.053	.048				
2.0	.062	.039					.065	
2.2			.045	.055	.075			
2.4	.059					.097		.106
2.6		.067						
2.8	.077		.064	.102			.079	.091
3.0		.063			.096			
3.2								
3.4								.054
3.6		.043		.075		.077	.071	
3.8	.074				.087			
4.0		.087	.095	.077		.086	.084	.096
4.2								
4.4								
4.6		.080			.078			.084
4.8	.065		.095			.074	.084	
5.0				.082	.064			
5.2						.044		.079
5.4								
5.6	.056	.034		.034				
5.8			.062		.068		.044	
6.0	.067			.048				
6.2		.060			.066	.067		.047
6.4								
6.6							.033	
6.8	.036		.033					
7.0				.036	.064	.026		

No. Sample Intervals	222	222	218	220	241	220	218	220
Average	7.61	7.68	7.45	7.33	6.66	7.68	6.16	7.42
Number Intervals	338	415	419	440	561	431	478	660
Vowel Location	3A(4)	3A(4)	7B(3)	7B(3)	8B(2)	8B(2)	4A(3)	4A(3)
Intensity	10	10	10	10	20	20	40	40

TABLE 10

STIMULUS INTERVALS TABLE
VOWEL /a/

INTERVAL	STIMULUS				
	3A	7B	8B	4A	
.2	0	0	0	0	
.4	0	0	0	0	
.6	1	3	2	0	
.8	4	2	5	0	
1.0	11	10	7	13	
1.2	10	8	13	11	
1.4	12	14	12	0	
1.6	5	2	2	9	
1.8	2	4	4	0	
2.0	6	2	0	9	
2.2	7	9	0	2	
2.4	6	6	0	2	
2.6	13	6	10	7	
2.8	9	12	11	11	
3.0	1	3	0	6	
3.2	5	0	2	2	
3.4	2	3	7	0	
3.6	12	6	9	7	
3.8	4	9	4	9	
4.0	12	6	10	11	
4.2	3	6	0	0	
4.4	0	0	0	0	
4.6	7	7	2	5	
4.8	9	7	12	11	
5.0	9	10	6	9	
5.2	6	7	9	2	
5.4	4	3	0	0	
5.6	3	6	2	4	
5.8	4	4	0	5	
6.0	7	2	6	10	
6.2	7	2	0	4	
6.4	2	6	0	2	
6.6	2	0	0	7	
6.8	0	0	0	2	
7.0	0	0	0	0	
7.2	0	0	0	0	
7.4	0	0	0	0	
7.6	0	0	0	0	
7.8	0	0	0	0	
8.0	0	0	0	0	

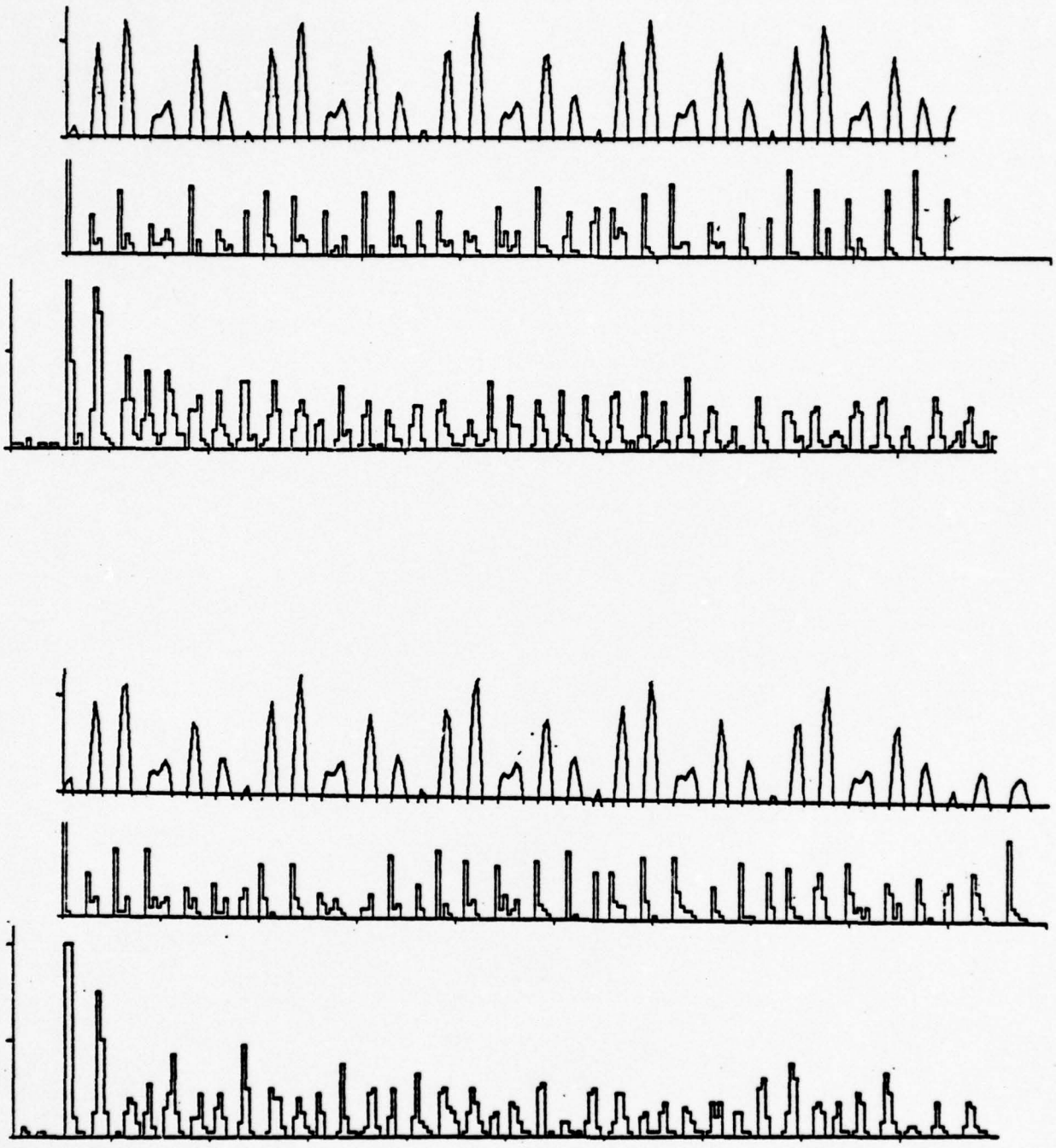


Figure 20. /ɔ/-POHs from neuron 710827/11 (lower curve in (a) and (b)) and Model 08/13/76 (middle curve in (a) and (b)) and corresponding segment from the ROC COC2 response, positive values only (upper curve in (a) and (b)). In (a) the neuron run is 7, the model run is 08/13/76.1/2, and the stimulus is 3B, presented at an intensity of 10 dB attenuation. In (b) the neuron run is 14, the model run is 08/13/76.2/1, and the stimulus is 7A, presented at an intensity of 10 dB attenuation.

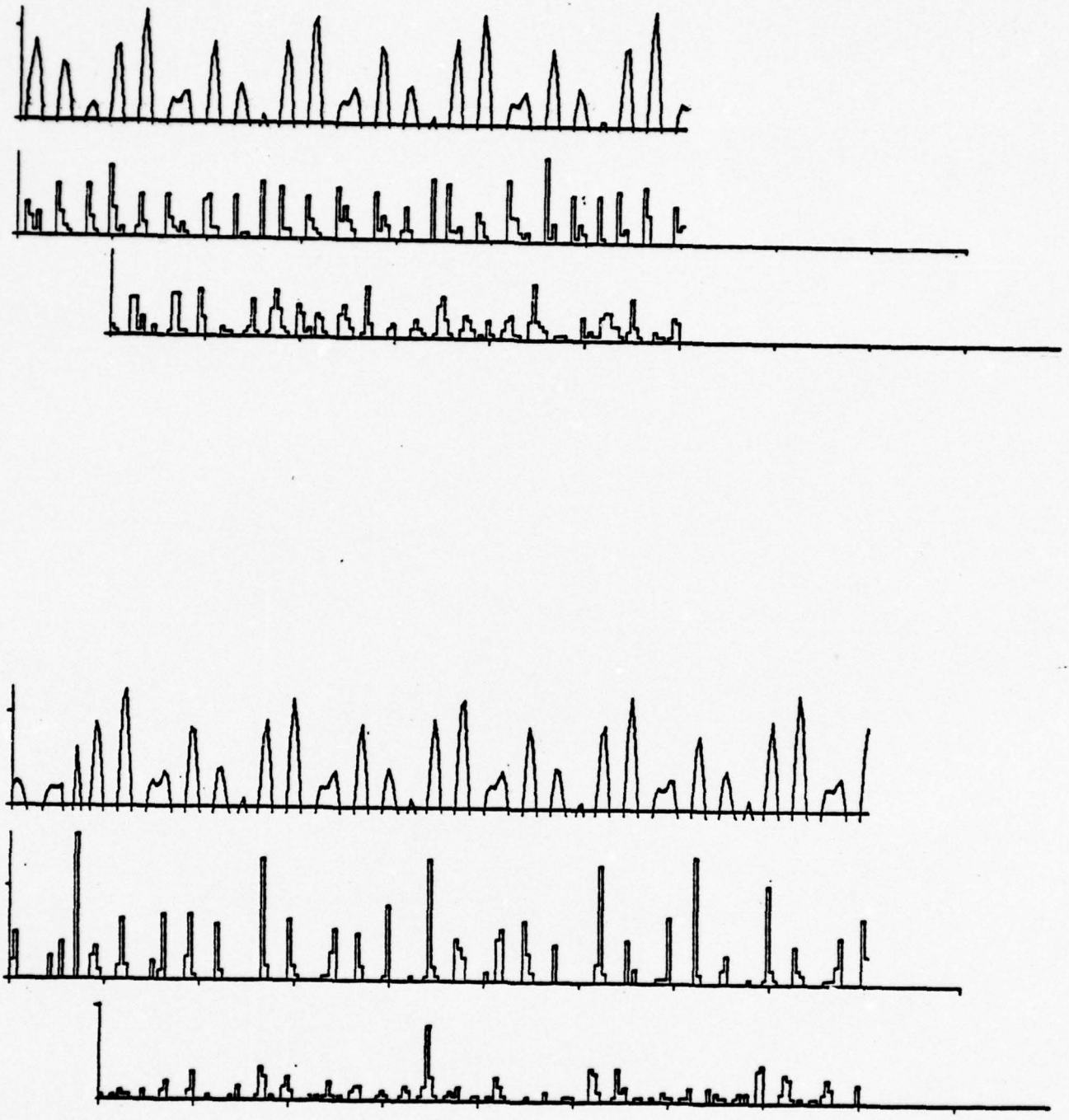


Figure 21. /ɔ/-POHs from neuron 710827/11 (lower curve in (a) and (b)) and Model 08/13/76 (middle curve in (a) and (b)) and corresponding segment from the ROC COC2 response, positive values only (upper curve in (a) and (b)). In (a) the neuron run is 16, the model run is 08/13/76.2/3, and the stimulus is 8A, presented at an intensity of 20 dB attenuation. In (b) the neuron run is 9, the model run is 08/13/76.1/4, and the stimulus is 4B, presented at an intensity of 40 dB attenuation.

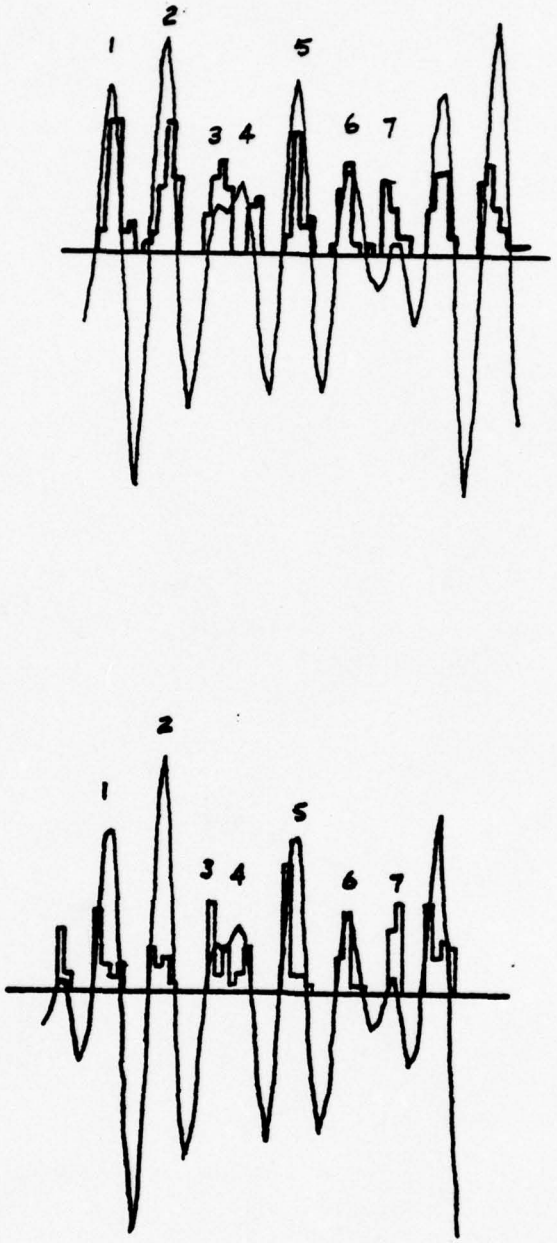


Figure 22. A pitch period of the vowel /ɔ/ superimposed on a typical corresponding segment of a 10 dB /ɔ/-POH. (a) is neuron 710827, Run 7. (b) is Model run 08/13/76.1/2.

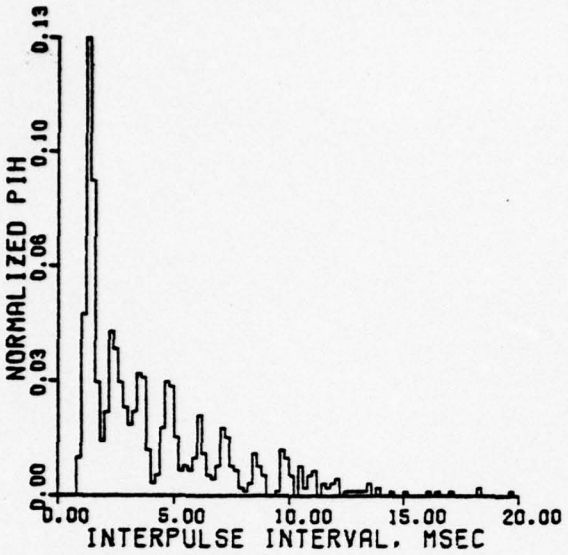


FIGURE 710827 . 11.. 7.
DEFINING INTERVALS 15 TO 233
AVERAGE = 4.38 NUMBER OF INTERVALS = 842

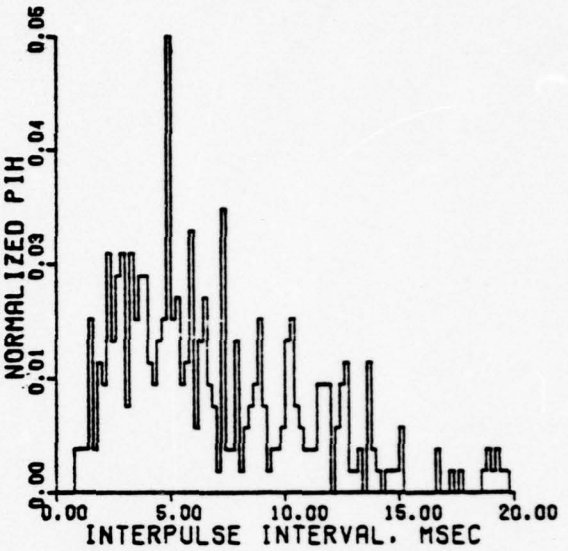


FIGURE LEET. 0 . 08/13/76.1. 2.
DEFINING INTERVALS 15 TO 225
AVERAGE = 7.71 NUMBER OF INTERVALS = 388

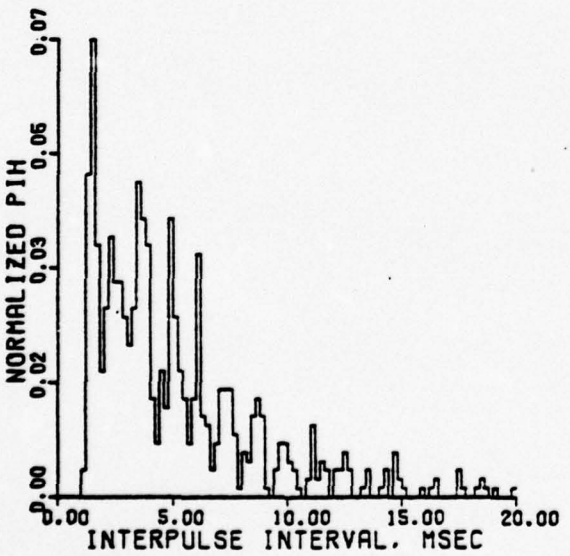


FIGURE 710827 . 11.. 14.
DEFINING INTERVALS 12 TO 237
AVERAGE = 5.23 NUMBER OF INTERVALS = 742

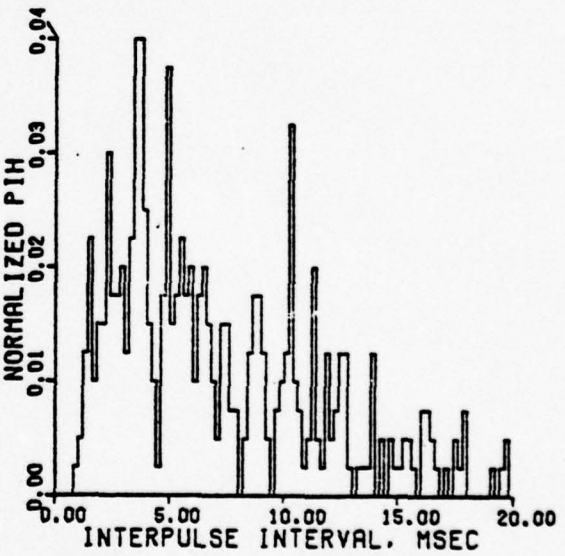


FIGURE LEET. 0 . 08/13/76.2 1.
DEFINING INTERVALS 12 TO 227
AVERAGE = 7.86 NUMBER OF INTERVALS = 394

Figure 23. /ɔ/-PIHs of neuron 710827/11 and Model 08/13/76 corresponding to the /ɔ/-POHs of Figure 20. (a) neuron run 7, (b) model run 08/13/76.1/2, (c) neuron run 14, and (d) model run 08/13/76.2/1.

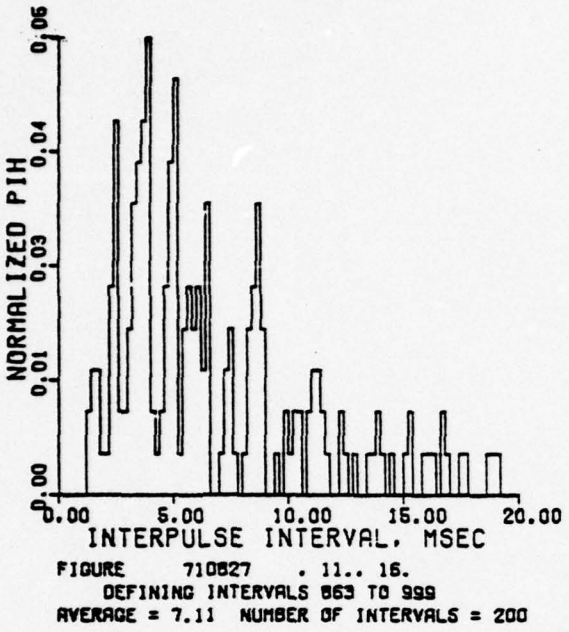


FIGURE 710827 . 11.. 16.
DEFINING INTERVALS 863 TO 999
AVERAGE = 7.11 NUMBER OF INTERVALS = 200

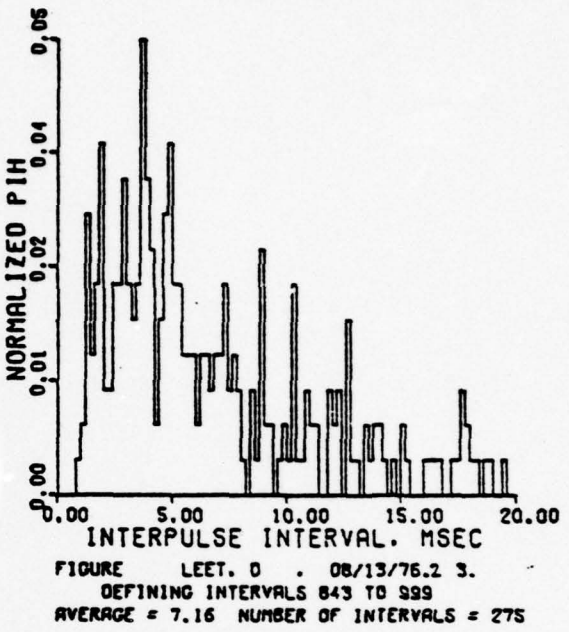


FIGURE LEET. 0 . 08/13/76.2 3.
DEFINING INTERVALS 843 TO 999
AVERAGE = 7.16 NUMBER OF INTERVALS = 275

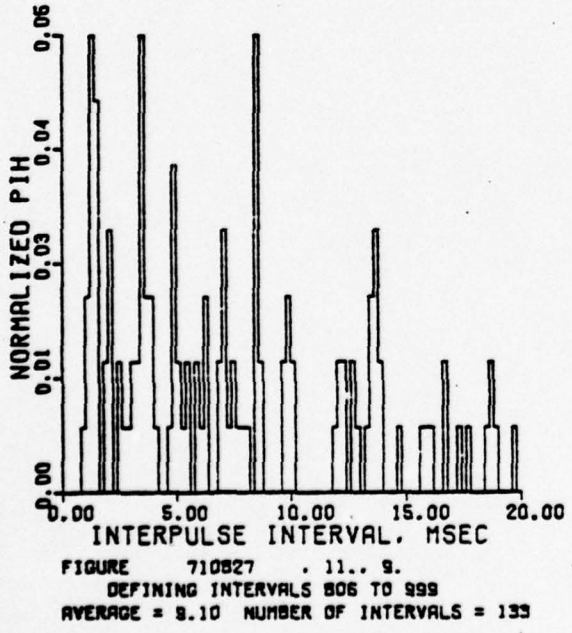


FIGURE 710827 . 11.. 9.
DEFINING INTERVALS 806 TO 999
AVERAGE = 9.10 NUMBER OF INTERVALS = 133

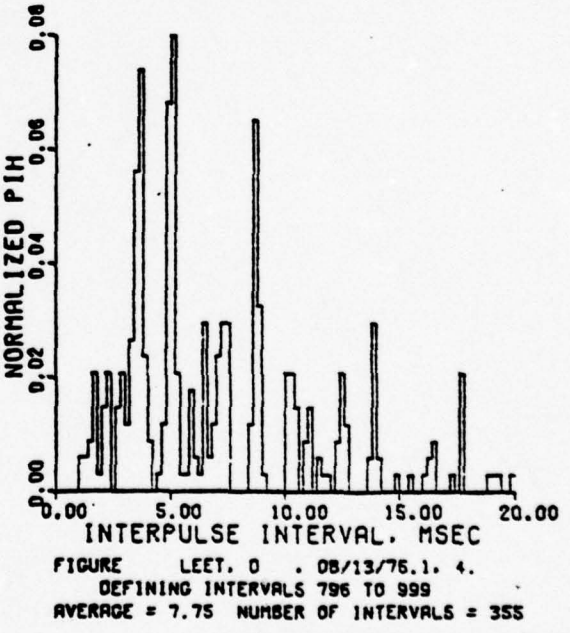


FIGURE LEET. 0 . 08/13/76.1. 4.
DEFINING INTERVALS 796 TO 999
AVERAGE = 7.75 NUMBER OF INTERVALS = 355

Figure 24. /ɔ/-PIHs of neuron 710827/11 and Model 08/13/76 corresponding to the /ɔ/-POHs of Figure 21. (a) neuron run 16, (b) model run 08/13/76.2/3, (c) neuron run 9, and (d) model run 08/13/76.1/4.

TABLE 11

PEAK OCCURRENCE TABLE - VOWEL /ɔ/

Interpulse Interval	710827/11 Run 7	08/13/76.1 Run 2	710827/11 Run 14	08/13/76.2 Run 1	710827/11 Run 16	08/13/76.2 Run 3	710827/11 Run 9	08/13/76.1 Run 4
1.2								
1.4	.270				.040	.051	.120	
1.6		.031	.155	.046				
1.8								.031
2.0		.034				.069		
2.2							.045	
2.4	.112	.059	.100	.063				.034
2.6					.080		.023	
2.8								
3.0		.064		.051		.076		.045
3.2								
3.4		.059						
3.6	.091		.117				.090	
3.8		.072		.107		.102		.146
4.0					.100			
4.2								
4.4								
4.6			.040					
4.8	.082							
5.0		.095	.082	.071		.087	.060	
5.2					.095			.161
5.4		.057						
5.6				.058				
5.8					.065			
6.0		.054		.048				.025
6.2	.046		.063		.060			
6.4								
6.6		.054		.053	.050	.040	.023	.037
6.8								
7.0							.023	

No. Sample Intervals	218	211	226	216	137	157	194	204
Average	4.38	7.71	5.23	7.86	7.11	7.16	9.10	7.75
Number Intervals	842	388	742	394	200	275	133	355
Vowel Location	3B(1)	3B(1)	7A(1)	7A(1)	8A(5)	8A(5)	4B(5)	4B(5)
Intensity	10	10	10	10	20	20	40	40

TABLE 12

STIMULUS INTERVALS TABLE
VOWEL /ɔ/

INTERVAL	STIMULUS			
	3B	7A	8A	4B
.2	0	0	0	0
.4	0	0	0	0
.6	0	0	0	0
.8	1	0	0	0
1.0	3	4	3	0
1.2	0	1	0	0
1.4	14	11	9	7
1.6	6	8	5	6
1.8	0	0	0	0
2.0	5	4	2	3
2.2	2	2	1	4
2.4	5	5	5	1
2.6	1	2	1	0
2.8	4	4	2	1
3.0	6	5	5	2
3.2	0	1	0	1
3.4	5	2	1	2
3.6	6	8	5	8
3.8	7	7	4	5
4.0	4	4	5	1
4.2	0	1	0	0
4.4	0	0	0	0
4.6	0	0	0	0
4.8	4	3	1	0
5.0	11	8	6	6
5.2	4	6	3	5
5.4	4	6	5	5
5.6	0	0	0	0
5.8	5	3	1	3
6.0	3	3	3	0
6.2	0	2	1	0
6.4	9	5	3	1
6.6	1	5	3	3
6.8	4	3	2	4
7.0	0	1	1	0
7.2	6	1	0	2
7.4	9	10	7	9
7.6	1	5	3	0
7.8	4	2	1	0
8.0	1	3	2	0

3.7 THE VOWEL /æ/

The neuron /æ/-POHs are aligned with their respective model /æ/-POHs and ROC COC2 response segments in Figures 25 and 26.

A pitch period from /æ/ is superimposed in Figure 27 on typical corresponding segments of neuron on model /æ/-POHs. The correlation between the location of the pitch period, neuron /æ/-POH and model /æ/-POH peaks is good. The model and neuron /æ/-PIH peak locations also correlate well.

3.8 THE VOWEL /o/

The neuron /o/-POHs are aligned with their corresponding model /o/-POHs and ROC COC2 response segments in Figures 30 and 31.

In Figure 32, a typical pitch period from the ROC COC2 response at 10 dB attenuation is superimposed on the corresponding segment of the neuron /o/-POH, Run 7, and the model /o/-POH, Run 08/13/76.1/2. There are two significant differences between the responses of the neuron and the model. First, the first neuron /a/-POH peak corresponding to ROC COC2 response peak 2 is generally smaller than the same peak in the model /a/-POH. Second, the neuron /a/-POH consistently has a peak corresponding to peak 4 of the ROC COC2 response. The model /a/-POH does not. This difference is reflected in the /o/-PIHs, Figures 33 and 34, where there is a peak at 4.0 msec only in the Model /o/-PIH. This peak can be associated with the time interval between the positive zero-crossing points of peaks 2 and 5 in the ROC COC2 pitch period. The neuron is apparently firing at peak 4 instead of peak 5.

3.9 THE VOWEL /ɛ/

The neuron /ɛ/-POHs are aligned with their corresponding model /ɛ/-POHs and ROC COC2 response segments in Figures 35 and 36.

In Figure 37 a pitch period of /ɛ/ is superimposed on typical corresponding segments of the 10 dB /ɛ/-POH from neuron Run 6 and model Run

Text continued on page 78

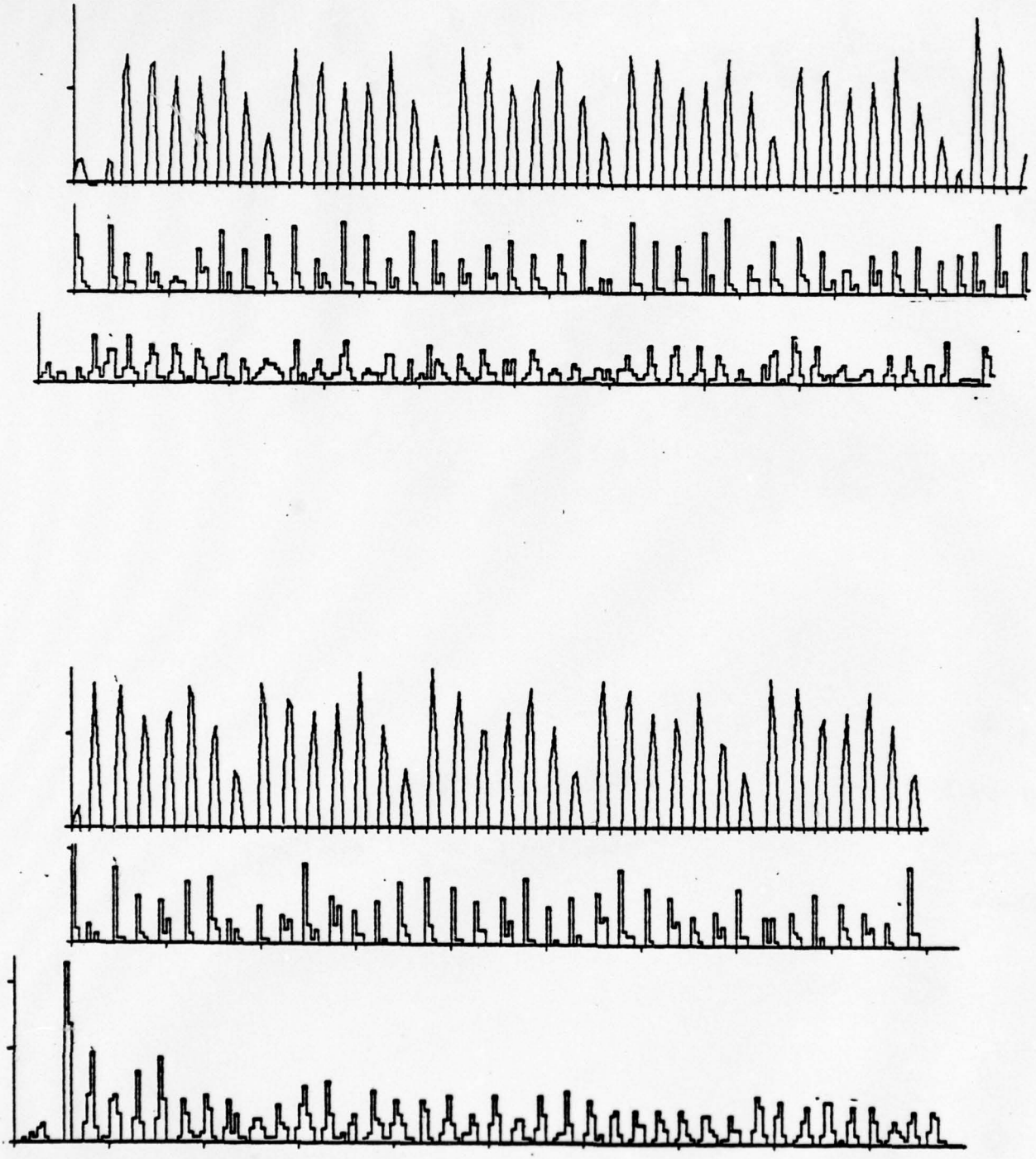


Figure 25. /æ/-POHs from neuron 710827/11 (lower curve in (a) and (b)) and Model 08/13/76 (middle curve in (a) and (b)) and corresponding segment from the ROC COC2 response, positive values only (upper curve in (a) and (b)). In (a) the neuron run is 6, the model run is 08/13/76.1/1, and the stimulus is 3A, presented at an intensity of 10 dB attenuation. In (b) the neuron run is 15, the model run is 08/13/76.2/2, and the stimulus is 7B, presented at an intensity of 10 dB attenuation.

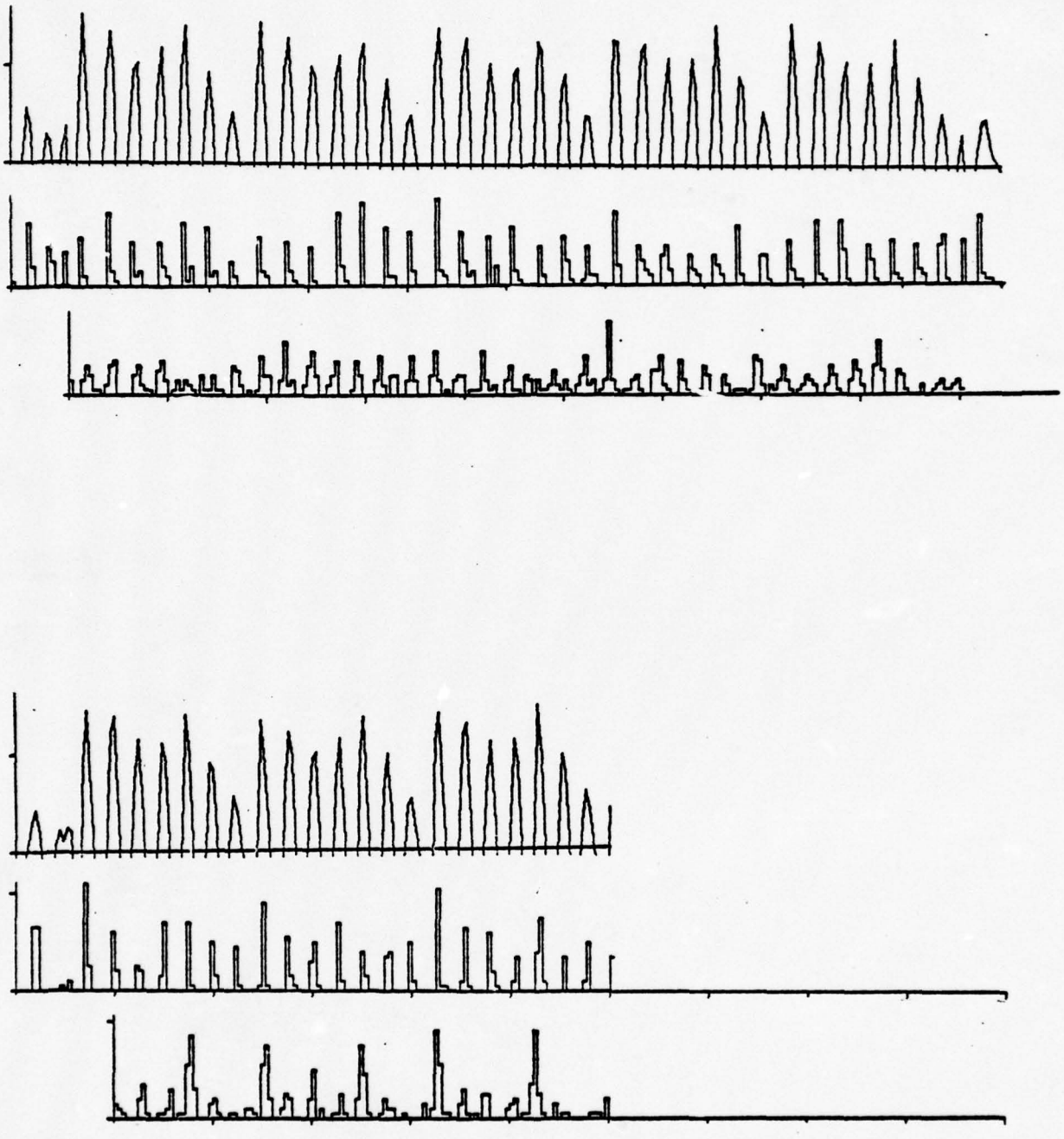


Figure 26. /æ/-POHs from neuron 710827/11 (lower curve in (a) and (b)) and Model 08/13/76 (middle curve in (a) and (b)) and corresponding segment from the ROC COC2 response, positive values only (upper curve in (a) and (b)). In (a) the neuron run is 17, the model run is 08/13/76.2/4, and the stimulus is 8B, presented at an intensity of 20 dB attenuation. In (b) the neuron run is 8, the model run is 08/13/76.1/3, and the stimulus is 4A, presented at an intensity of 40 dB attenuation.

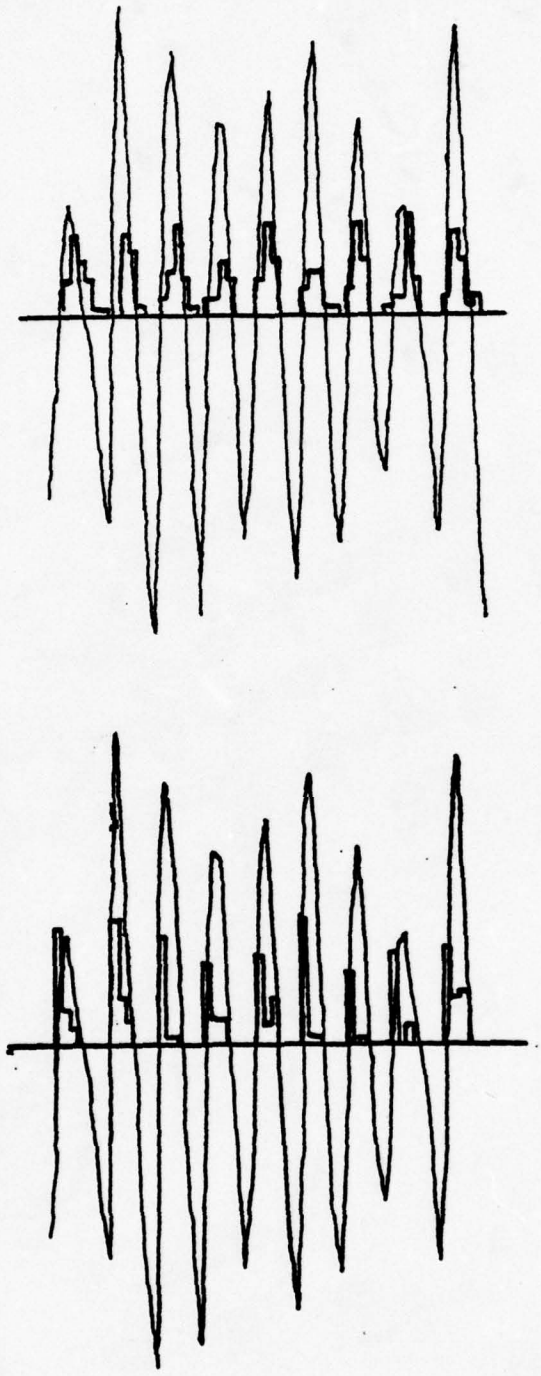


Figure 27. A pitch period of the vowel /æ / superimposed on a typical corresponding segment of a 10 dB /æ /-POH. (a) is neuron 710827/11, Run 15. (b) is model run 08/13/76.2/2.

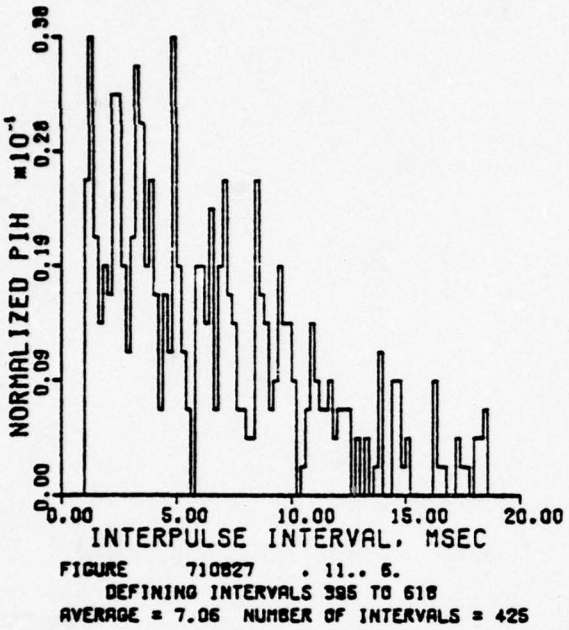


FIGURE 710827 . 11.. 6.
DEFINING INTERVALS 395 TO 618
AVERAGE = 7.06 NUMBER OF INTERVALS = 425

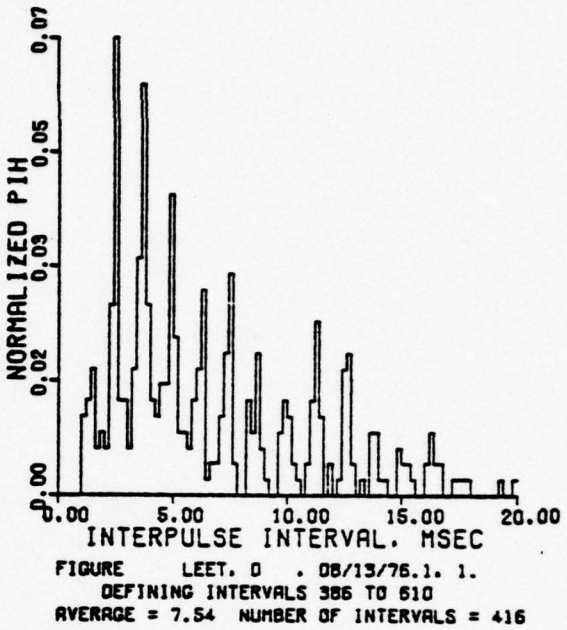


FIGURE LEET. D . 08/13/76.1. 1.
DEFINING INTERVALS 386 TO 610
AVERAGE = 7.54 NUMBER OF INTERVALS = 416

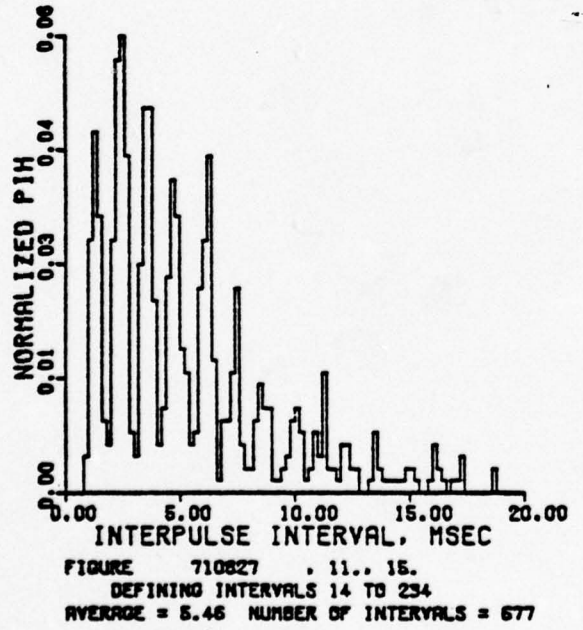


FIGURE 710827 . 11.. 15.
DEFINING INTERVALS 14 TO 234
AVERAGE = 5.46 NUMBER OF INTERVALS = 677

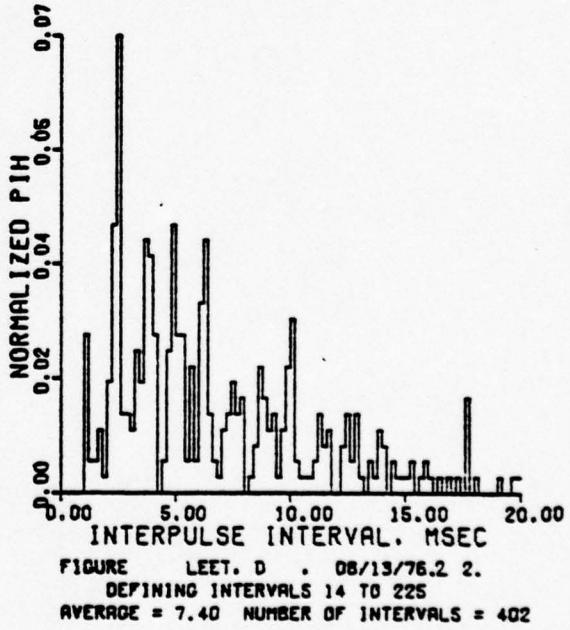


FIGURE LEET. D . 08/13/76.2 2.
DEFINING INTERVALS 14 TO 225
AVERAGE = 7.40 NUMBER OF INTERVALS = 402

Figure 28. /æ/-PIHs of neuron 710827/11 and Model 08/13/76 corresponding to the /æ/-POHs of Figure . (a) neuron run 6, (b) model run 08/13/76.1/1, (c) neuron run 15, and (d) model run 08/13/76.2/2.

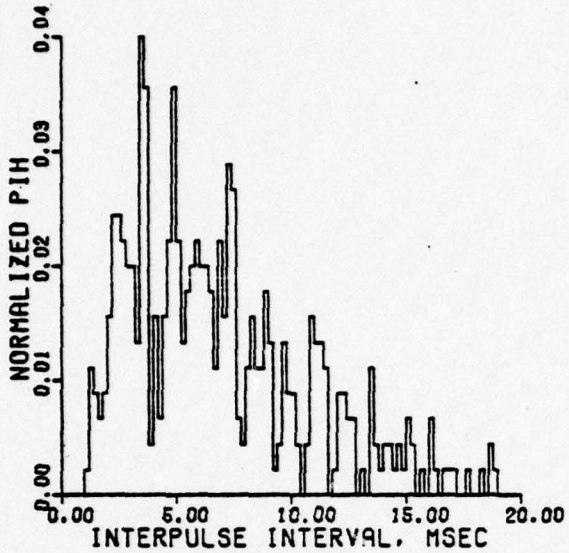


FIGURE 710827 . 11.. 17.
DEFINING INTERVALS 454 TO 674
AVERAGE = 7.41 NUMBER OF INTERVALS = 424

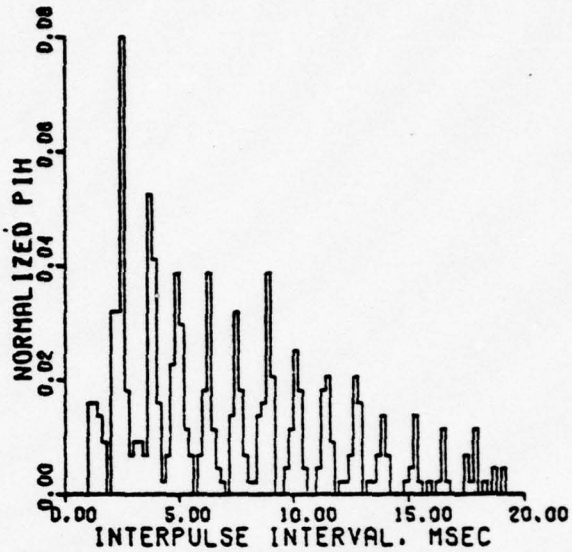


FIGURE LEET. 0 . 08/13/76.2 4.
DEFINING INTERVALS 436 TO 665
AVERAGE = 7.58 NUMBER OF INTERVALS = 448

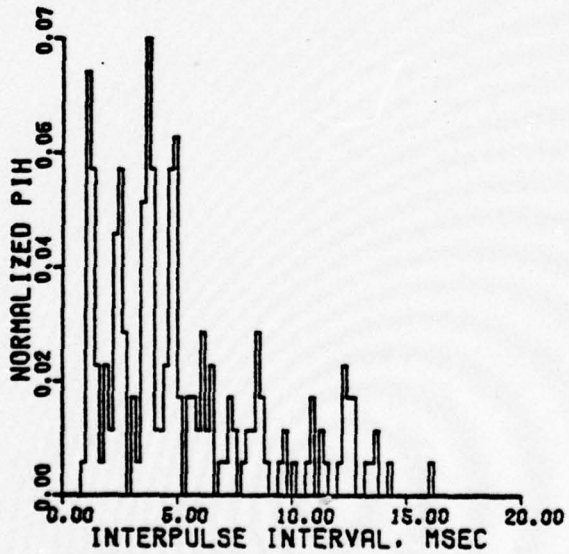


FIGURE 710827 . 11.. 8.
DEFINING INTERVALS 880 TO 999
AVERAGE = 5.29 NUMBER OF INTERVALS = 195

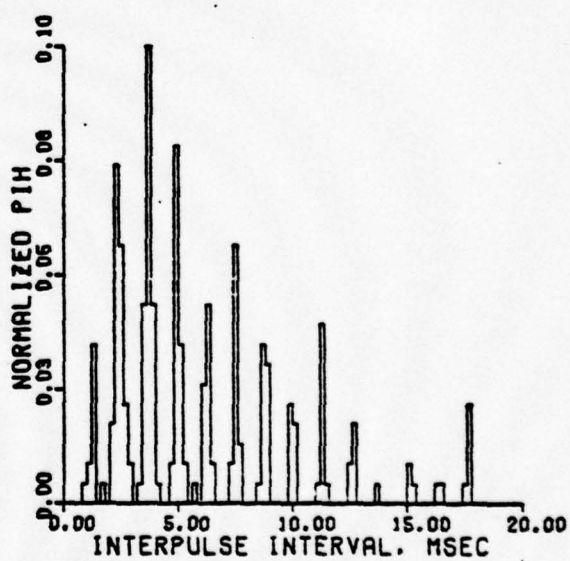


FIGURE LEET. 0 . 08/13/76.1. 3.
DEFINING INTERVALS 866 TO 999
AVERAGE = 6.31 NUMBER OF INTERVALS = 222

Figure 29. /ae/-PIHs of neuron 710827/11 and Model 08/13/76 corresponding to the /ae/-POHs of Figure . (a) neuron run 17, (b) model run 08/13/76.2/4, (c) neuron run 8, and (d) model run 08/13/76.1/3.

TABLE 13

PEAK OCCURRENCE TABLE - VOWEL /æ/

Interpulse Interval	710827/11 Run 6	08/13/76.1 Run 1	710827/11 Run 15	08/13/76.2 Run 2	710827/11 Run 17	08/13/76.2 Run 4	710827/11 Run 8	08/13/76.1 Run 3
1.0								
1.2				.030			.123	
1.4	.085		.109		.024	.045		.045
1.6		.041						
1.8				.017				.005
2.0	.049	.024					.036	
2.2								
2.4								.153
2.6	.085	.113		.127	.075	.127	.118	
2.8			.151					
3.0								
3.2							.021	
3.4	.087		.123	.050		.025		
3.6					.094			
3.8		.127		.095		.098	.169	.194
4.0	.061							
4.2					.028			
4.4								
4.6	.035							
4.8			.099					
5.0	.068	.087		.090	.085	.089	.123	.126
5.2								
5.4								
5.6			.033					
5.8				.030			.041	.005
6.0					.066			
6.2	.052						.046	
6.4		.053	.089	.082		.067		081
6.6	.045						.031	
6.8								
7.0								

No. Sample Intervals	224	225	221	212	221	230	120	134
Average	7.06	7.54	5.46	7.40	7.41	7.58	5.29	6.31
Number Intervals	425	416	677	402	424	448	195	222
Vowel Location	3A(3)	3A(3)	7B(1)	7B(1)	8B(3)	8B(3)	4A(5)	4A(5)
Intensity	10	10	10	10	20	20	40	40

TABLE 14

STIMULUS INTERVALS TABLE
VOWEL /æ/

INTERVAL	STIMULUS			
	3A	7B	8B	4A
.2	0	0	0	0
.4	0	0	0	0
.6	0	0	0	0
.8	0	0	1	0
1.0	3	1	2	1
1.2	21	21	20	13
1.4	11	11	12	5
1.6	1	1	1	1
1.8	0	0	0	0
2.0	0	0	0	0
2.2	3	1	3	1
2.4	12	11	9	7
2.6	16	18	20	9
2.8	4	3	3	2
3.0	0	0	0	0
3.2	0	0	0	0
3.4	2	0	2	0
3.6	6	6	4	3
3.8	21	18	19	12
4.0	3	8	9	3
4.2	2	0	0	0
4.4	0	0	0	0
4.6	2	0	1	0
4.8	4	2	2	1
5.0	17	16	14	10
5.2	6	10	14	5
5.4	3	3	2	1
5.6	1	0	0	0
5.8	1	0	0	0
6.0	5	1	2	1
6.2	10	9	7	5
6.4	10	15	18	8
6.6	4	5	5	2
6.8	2	0	0	0
7.0	0	0	0	0
7.2	0	0	0	0
7.4	0	0	0	0
7.6	0	0	0	0
7.8	0	0	0	0
8.0	0	0	0	0

TABLE 15

PEAK OCCURRENCE TABLE - VOWEL /o/

Interpulse Interval	710827/11 Run 7	08/13/76.1 Run 2	710827/11 Run 15	08/13/76.2 Run 2	710827/11 Run 16	08/13/76.2 Run 3	710827/11 Run 8	08/13/76.1 Run 3
1.0								
1.2							.053	
1.4	.089		.022			.045		.018
1.6		.050		.049	.028			
1.8			.044				.026	.035
2.0	.079	.056		.055				
2.2					.091	.085		.056
2.4	.099		.087				.035	
2.6		.058		.063				.047
2.8						.077		
3.0				.049	.042		.044	
3.2		.069						
3.4			.117			.074		
3.6	.091	.064		.060	.097			
3.8							.061	
4.0		.083			.053	.068		
4.2				.066				
4.4		.064	.087					
4.6	.058			.077				.103
4.8		.058				.068	.009	
5.0								
5.2				.074				
5.4							.026	
5.6	.083					.037		
5.8		.050	.061		.072			.111
6.0						.043	.009	
6.2		.058	.039	.060	.066			
6.4							.053	.053
6.6	.030							
6.8			.041		.047	.063		.032
7.0		.058		.036				

No. Sample Intervals	209	203	215	207	218	204	212	205
Average	6.51	7.46	7.22	7.68	7.65	7.45	11.21	7.99
Number Intervals	496	360	412	366	361	352	114	341
Vowel Location	3B(4)	3B(4)	7B(2)	7B(2)	8A(2)	8A(2)	4A(4)	4A(4)
Intensity	10	10	10	10	20	20	40	40

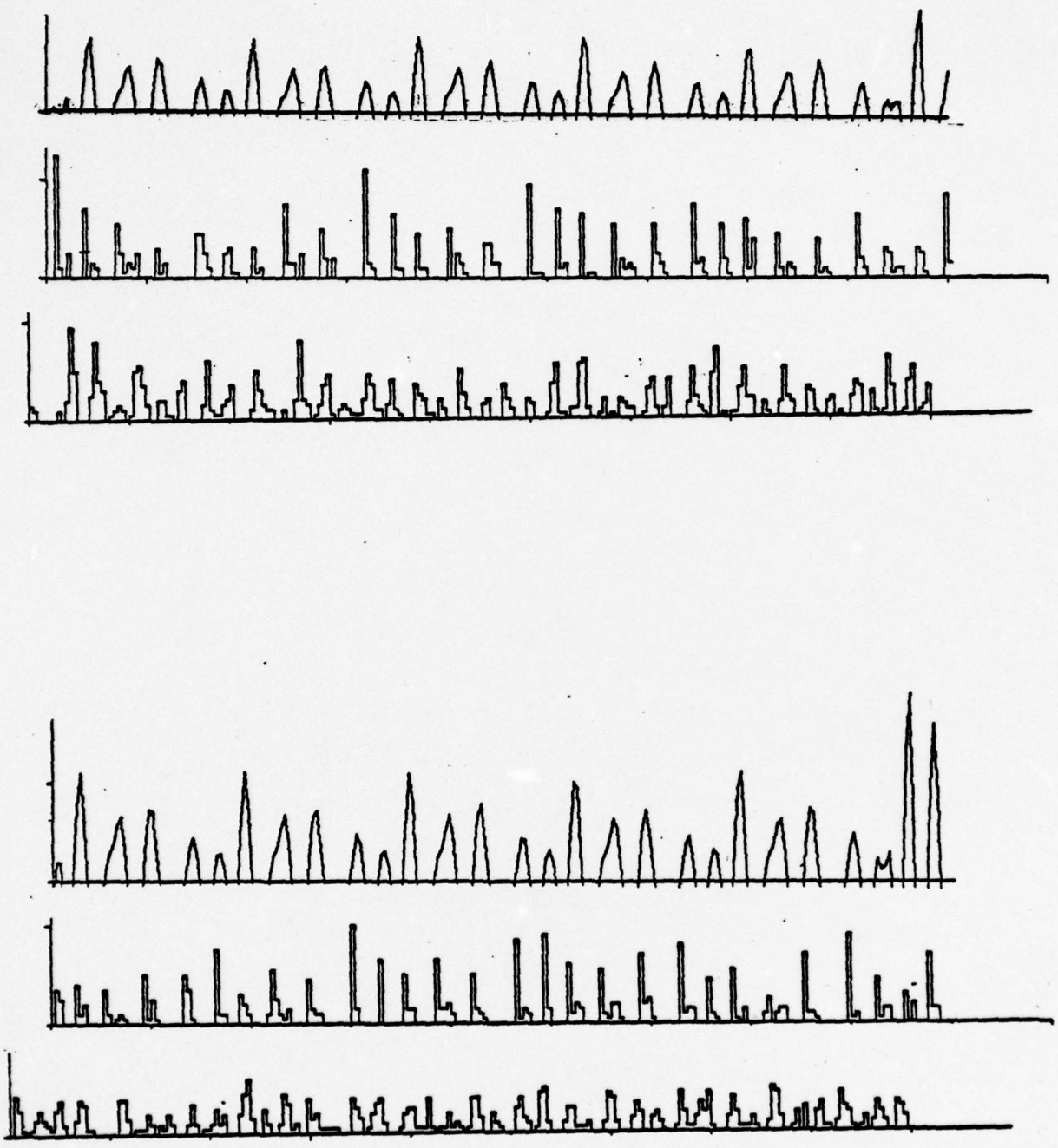


Figure 30. /o/-POHs from neuron 710827/11 (lower curve in (a) and (b)) and Model 08/13/76 (middle curve in (a) and (b)) and corresponding segment from the ROC COC2 response, positive values only (upper curve in (a) and (b)). In (a) the neuron run is 7, the model run is 08/13/76.1/2, and the stimulus is 3B, presented at an intensity of 10 dB attenuation. In (b) the neuron run is 15, the model run is 08/13/76.2/2, and the stimulus is 7B, presented at an intensity of 10 dB attenuation.

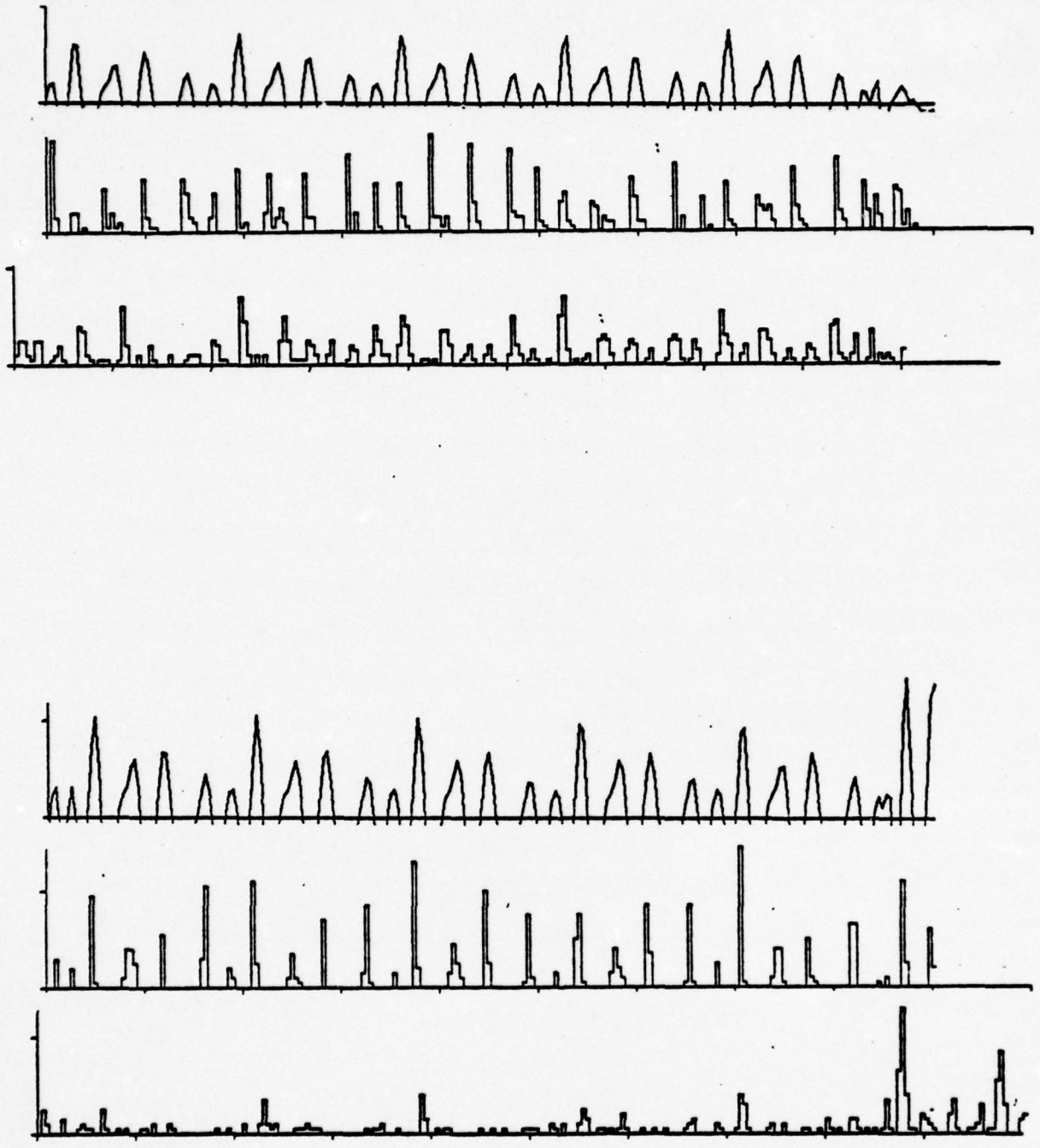


Figure 31. /o/-POHs from neuron 710827/11 (lower curve in (a) and (b)) and Model 08/13/76 (middle curve in (a) and (b)) and corresponding segment from the ROC COC2 response, positive values only (upper curve in (a) and (b)). In (a) the neuron run is 16, the model run is 08/13/76.2/3, and the stimulus is 8A, presented at an intensity of 20 dB attenuation. In (b) the neuron run is 8, the model run is 08/13/76.1/3, and the stimulus is 4A, presented at an intensity of 40 dB attenuation.

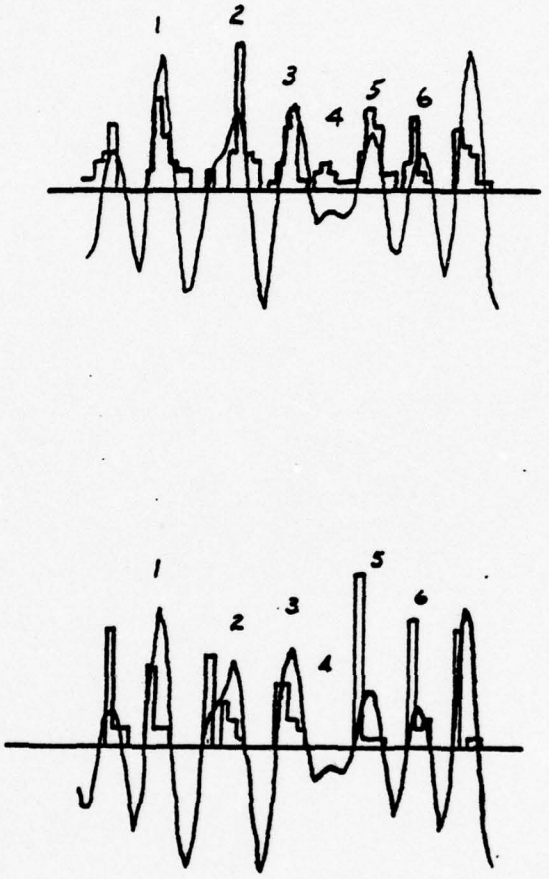
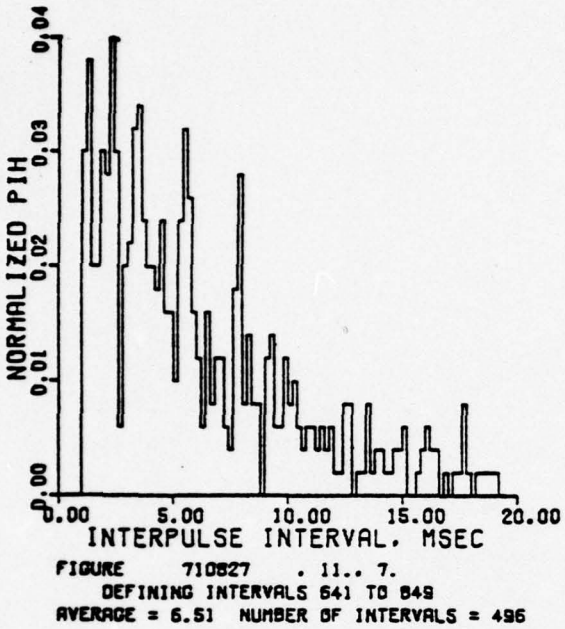
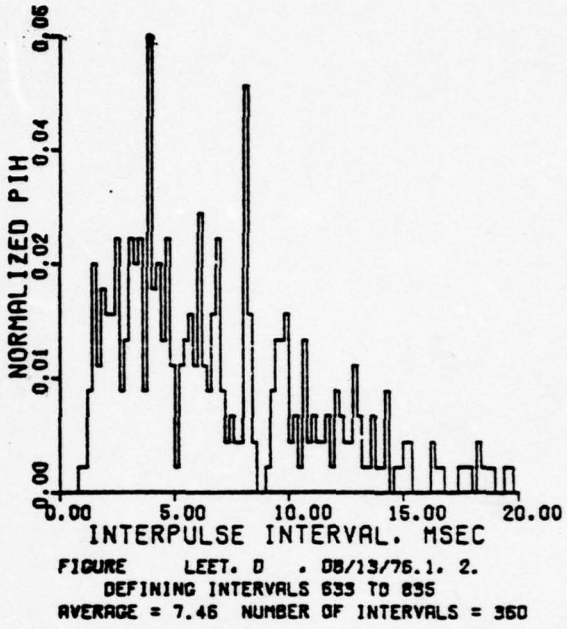
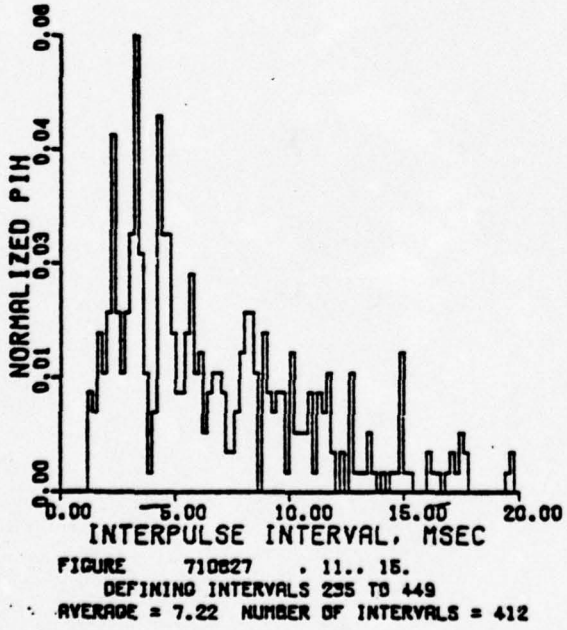


Figure 32. A pitch period of the vowel /o/ superimposed on a typical corresponding segment of a 10 dB /o/-POH. (a) is neuron 710827/11, Run 7, (b) is model Run 08/13/76.1/2.







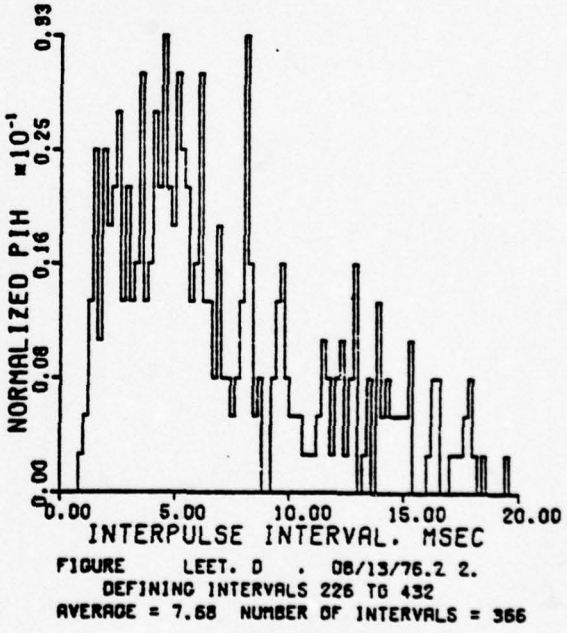


Figure 33. /o/-PIHs of Neuron 710827/11 and Model 08/13/76 corresponding to the /o/-POHs of Figure 30. (a) neuron run 7, (b) model run 08/13/76.1/2, (c) neuron run 15, and (d) model run 08/13/76.2/2.

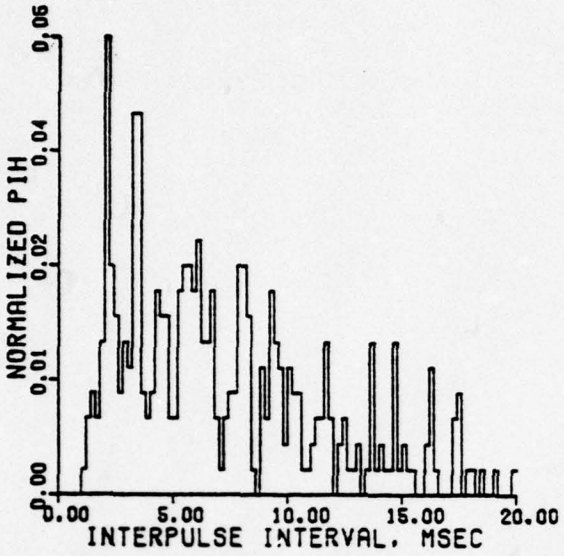


FIGURE 710827 . 11.. 16.
DEFINING INTERVALS 233 TO 450
AVERAGE = 7.65 NUMBER OF INTERVALS = 361

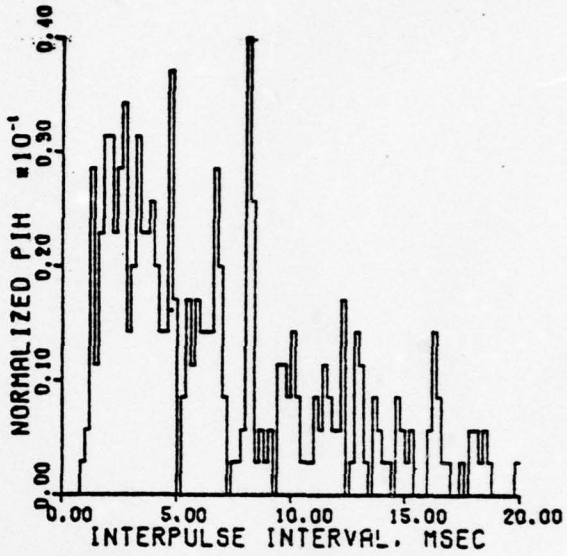


FIGURE LEET. 0 . 08/13/76.2 3.
DEFINING INTERVALS 229 TO 432
AVERAGE = 7.44 NUMBER OF INTERVALS = 352

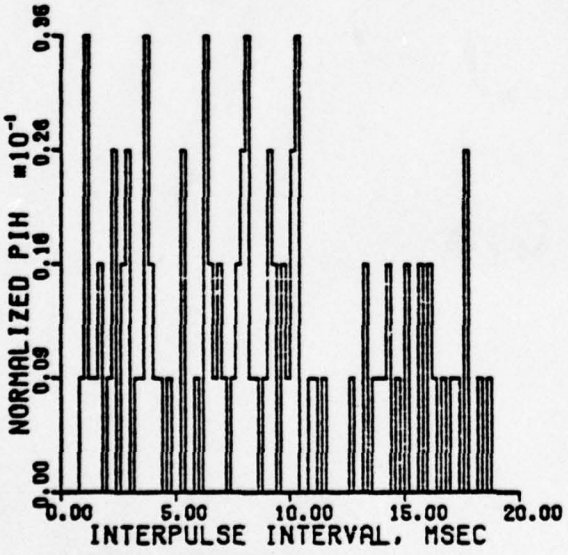


FIGURE 710827 . 11.. 8.
DEFINING INTERVALS 668 TO 879
AVERAGE = 11.21 NUMBER OF INTERVALS = 114

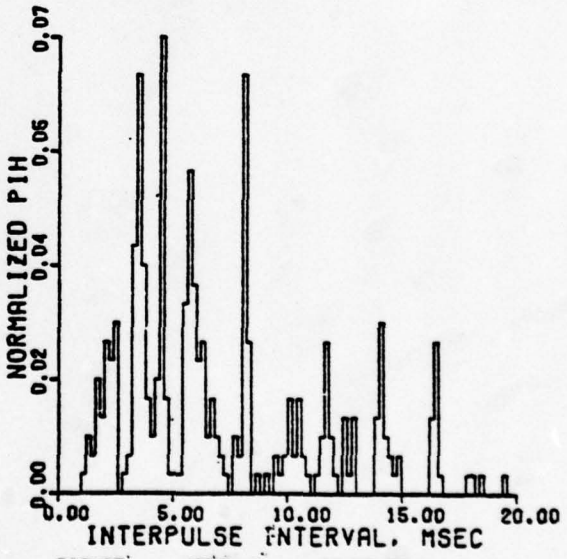


FIGURE LEET. 0 . 08/13/76.1. 3.
DEFINING INTERVALS 661 TO 865
AVERAGE = 7.99 NUMBER OF INTERVALS = 341

Figure 34. /o/-PIHs of Neuron 710827/11 and Model 08/13/76 corresponding to the /o/-POHs of Figure 31. (a) neuron run 16,(b) model run 08/13/76.2/3, (c) neuron run 8, and (d) model run 08/13/76.1/3.

TABLE 16

STIMULUS INTERVALS TABLE
VOWEL /o/

INTERVAL	STIMULUS			
	3B	7B	8A	4A
.2	0	0	0	0
.4	0	0	0	0
.6	0	0	0	0
.8	0	0	0	0
1.0	0	0	0	0
1.2	3	4	2	2
1.4	6	4	8	4
1.6	4	5	4	2
1.8	1	2	0	0
2.0	7	7	9	5
2.2	2	2	1	0
2.4	0	0	0	0
2.6	3	4	1	0
2.8	5	4	7	4
3.0	0	0	0	0
3.2	0	0	0	0
3.4	4	3	5	7
3.6	5	6	5	2
3.8	0	1	0	0
4.0	4	4	4	0
4.2	5	5	4	0
4.4	0	0	1	0
4.6	2	3	1	2
4.8	6	5	7	6
5.0	0	0	0	0
5.2	0	0	0	0
5.4	3	2	4	5
5.6	6	7	6	0
5.8	0	1	0	0
6.0	1	1	0	0
6.2	5	5	6	4
6.4	2	2	2	0
6.6	2	2	1	2
6.8	5	6	6	4
7.0	5	3	6	2
7.2	0	1	0	0
7.4	0	1	0	0
7.6	0	0	0	0
7.8	0	0	0	0
8.0	0	0	0	0

TABLE 17

PEAK OCCURRENCE TABLE - VOWEL /ɛ/

Interpulse Interval	710827/11 Run 6	08/13/76.1 Run 1	710827/11 Run 15	08/13/76.2 Run 2	710827/11 Run 17	08/13/76.2 Run 4	710827/11 Run 8	08/13/76.1 Run 3
1.0						.003		
1.2				.006				
1.4	.122		.043				.054	
1.6		.073		.067	.057			.076
1.8								
2.0			.069		.059	.081		
2.2		.043					.060	
2.4				.049				
2.6		.047				.040		
2.8	.052		.096	.049	.057			
3.0							.042	
3.2		.110						.163
3.4	.058			.091	.077	.121		
3.6								
3.8			.086		.074			
4.0								
4.2		.040		.079				
4.4	.047							
4.6							.054	
4.8		.107		.079	.072	.075		
5.0								.138
5.2	.064		.103	.073		.078		
5.4					.062		.030	
5.6								
5.8	.064	.020	.052			.024	.048	.008
6.0					.047			
6.2			.052			.016		
6.4								
6.6								
6.8		.073	.043	.079	.089			.106
7.0						.059	.054	

No. Sample Intervals	159	167	105	118	199	202	211	207
Average	7.26	7.22	6.81	6.84	6.70	7.24	9.62	7.69
Number Intervals	172	300	116	164	405	371	167	369
Vowel Location	3A(5)	3A(5)	7B(5)	7B(5)	8B(1)	8B(1)	4A(1)	4A(1)
Intensity	10	10	10	10	20	20	40	40

TABLE 18

STIMULUS INTERVALS TABLE
VOWEL /ɛ/

INTERVAL	STIMULUS			
	3A	7B	8B	4A
.2	0	0	0	0
.4	0	0	0	0
.6	0	0	0	0
.8	1	3	0	0
1.0	0	0	0	0
1.2	1	1	0	1
1.4	1	1	1	3
1.6	12	7	13	14
1.8	4	3	6	3
2.0	2	2	3	4
2.2	0	0	0	0
2.4	1	1	0	0
2.6	0	1	0	1
2.8	1	1	0	0
3.0	1	1	1	3
3.2	6	2	6	8
3.4	7	6	9	5
3.6	4	2	5	6
3.8	0	1	1	1
4.0	0	0	0	0
4.2	1	2	0	1
4.4	1	1	0	0
4.6	0	0	0	1
4.8	4	2	4	7
5.0	7	4	7	4
5.2	4	3	7	7
5.4	2	2	3	3
5.6	0	0	0	0
5.8	1	2	0	1
6.0	1	1	0	0
6.2	0	0	0	0
5.4	2	1	1	5
6.6	3	2	4	1
6.8	8	5	10	11
7.0	3	2	5	4
7.2	1	1	0	0
7.4	0	1	0	0
7.6	1	0	0	1
7.8	0	1	0	0
8.0	0	0	0	0

08/13/76. 1/1 (Figure 35a). The correlation shown is also typical of that found in the other 10 dB run (Figure 35b) and the 20 dB run (Figure 36a). The correlation between the neuron and model position of the histogram peaks with respect to the pitch period peaks is good. Generally the model histogram peaks are sharper than those of the neuron.

The /ɛ/-POHs do not provide any additional information. In part this is due to the fact that in all but the 20 dB run the number of intervals used to compute the histograms was too low for a reliable interpretation. (Evidence for this is the relatively low correlation in the location of the peaks between the two 10 dB neuron /ɛ/-PIHs.)

A final observation: The average firing rates for the two 10 dB and the 20 dB runs are acceptably close. The firing rate for the model 40 dB run is significantly greater than that of the corresponding neuron run.

3.10 THE VOWEL /I/

The neuron /I/-POHs are aligned with their respective model /I/-POHs and ROC COC2 response segments in Figures 40 and 41.

The consistent correspondence between pitch period and its /I/-POH segment is shown in Figure 42. The notable difference between the neuron and model activity is that neuron activity associated with pitch period peak 4 consistently occurs a couple of sample intervals earlier than the peak itself. This structure is also revealed in the neuron /I/-PIHs: peaks occur at 3.0-3.2 msec in the neuron /I/-PIHs, corresponding to the intervals between peaks in the neuron /I/-POH associated with pitch period peaks 1 and 4, but there are no such peaks in the model /I/-PIHs.

Furthermore, the interval between positive-slope zero-crossing points of peaks 4 and 1 is 3.6 msec and the corresponding interval between parts 1 and 4 is 5.6 msec. Both intervals show up as peaks in the model /I/-PIHs.

Text continued on page 91

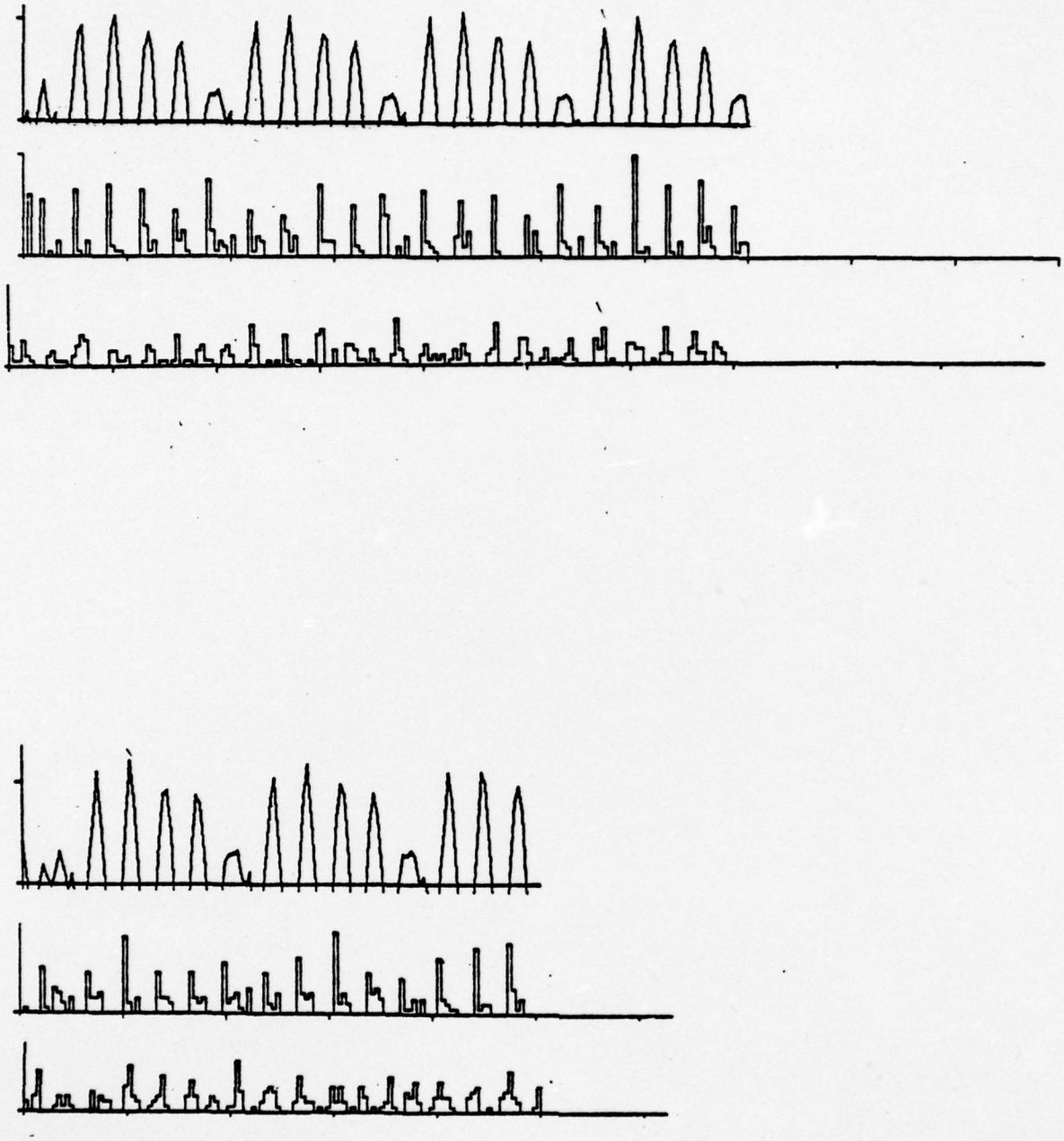


Figure 35. /ɛ/-POHs from neuron 710827/11 (lower curve in (a) and (b)) and Model 08/13/76 (middle curve in (a) and (b)) and corresponding segment from the ROC COC2 response, positive values only (upper curve in (a) and (b)). In (a) the neuron run is 6, the model run is 08/13/76.1/1, and the stimulus is 3A, presented at an intensity of 10 dB attenuation. In (b) the neuron run is 15, the model run is 08/13/76.2/2, and the stimulus is 7B, presented at an intensity of 10 dB attenuation.

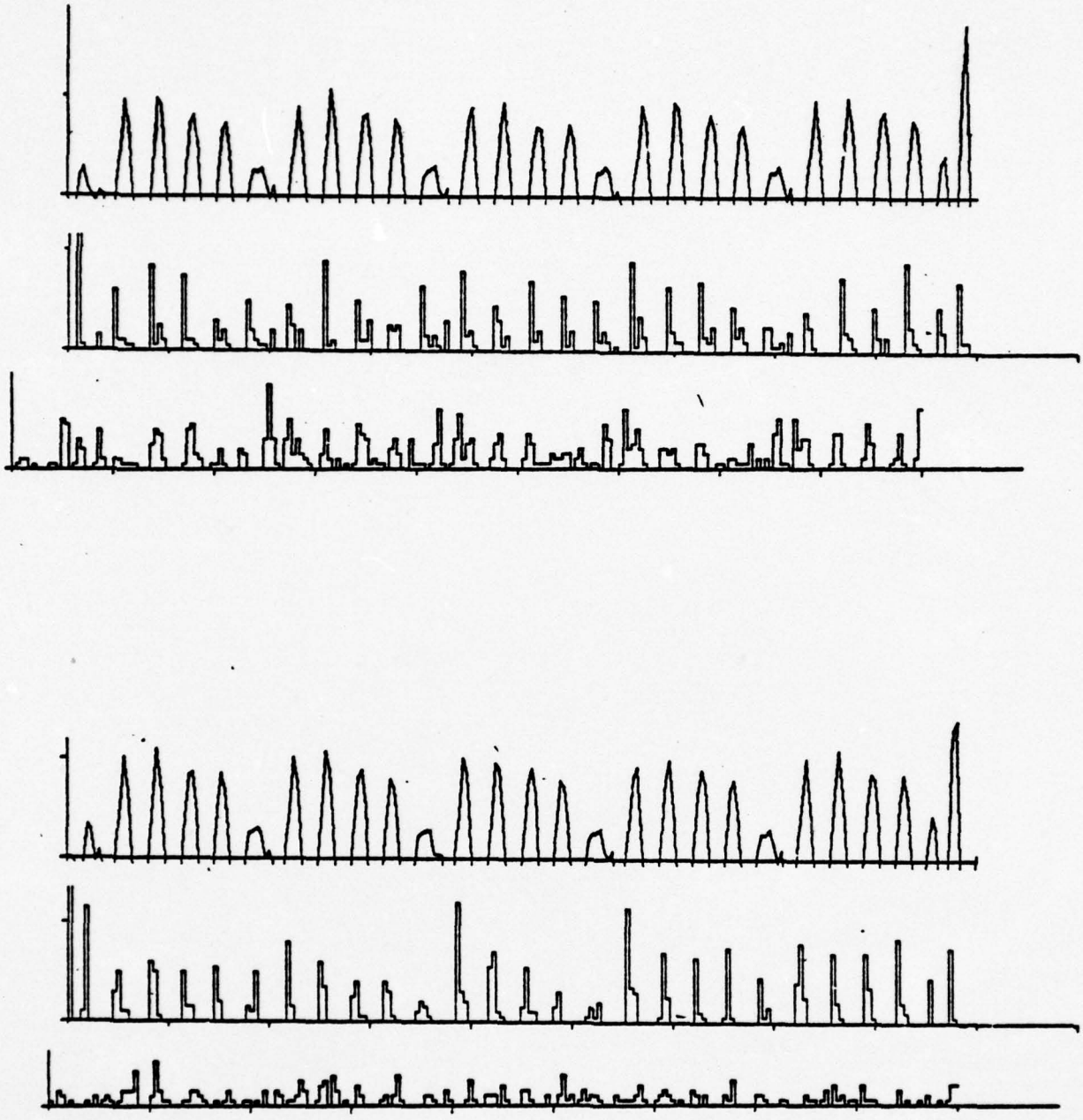


Figure 36. /ɛ/-POHs from neuron 710827/11 (lower curve in (a) and (b)) and Model 08/13/76 (middle curve in (a) and (b)) and corresponding segment from the ROC COC2 response, positive values only (upper curve in (a) and (b)). In (a) the neuron run is 17, the model run is 08/13/76.2/4, and the stimulus is 8B, presented at an intensity of 20 dB attenuation. In (b) the neuron run is 8, the model run is 08/13/76.1/3, and the stimulus is 4A, presented at an intensity of 40 dB attenuation.

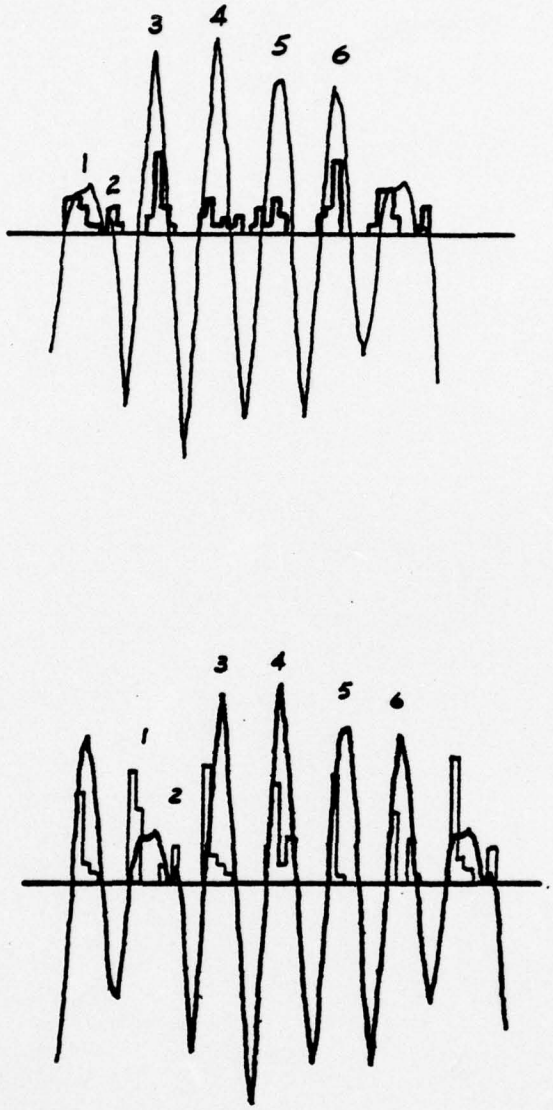


Figure 37. A pitch period of the vowel /ɛ/ superimposed on a typical corresponding segment of a 10 dB /ɛ/-POH. (a) is neuron 710827/11, Run 6, (b) is Model run 08/13/76.1/1.

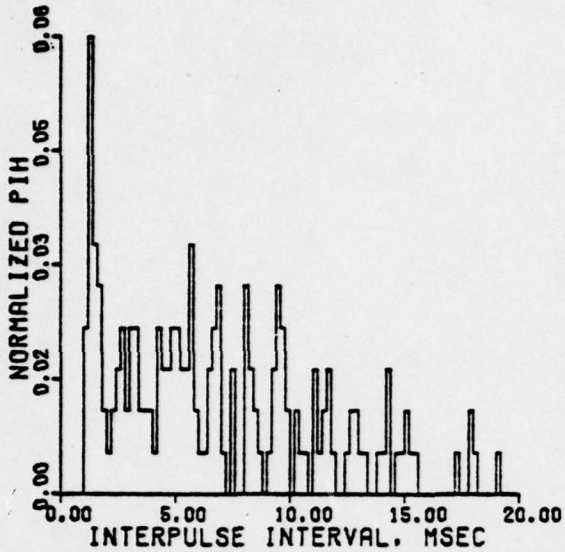


FIGURE 710827 . 11.. 6.
DEFINING INTERVALS 841 TO 999
AVERAGE = 7.26 NUMBER OF INTERVALS = 172

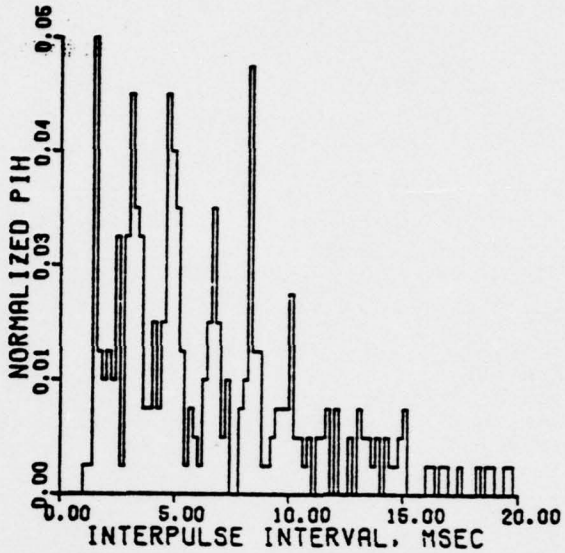


FIGURE LEET. 0 . 08/13/76.1. 1.
DEFINING INTERVALS 833 TO 999
AVERAGE = 7.22 NUMBER OF INTERVALS = 300

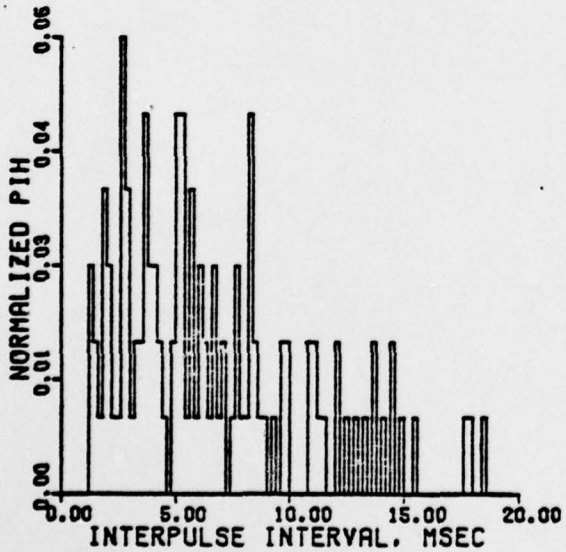


FIGURE 710827 . 11.. 15.
DEFINING INTERVALS 895 TO 999
AVERAGE = 6.81 NUMBER OF INTERVALS = 116

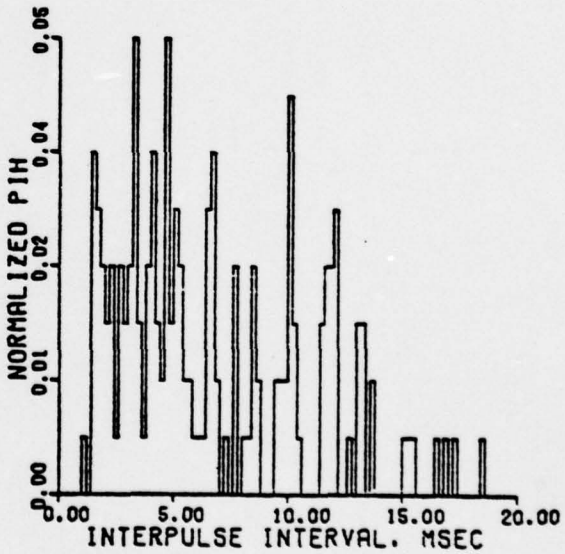
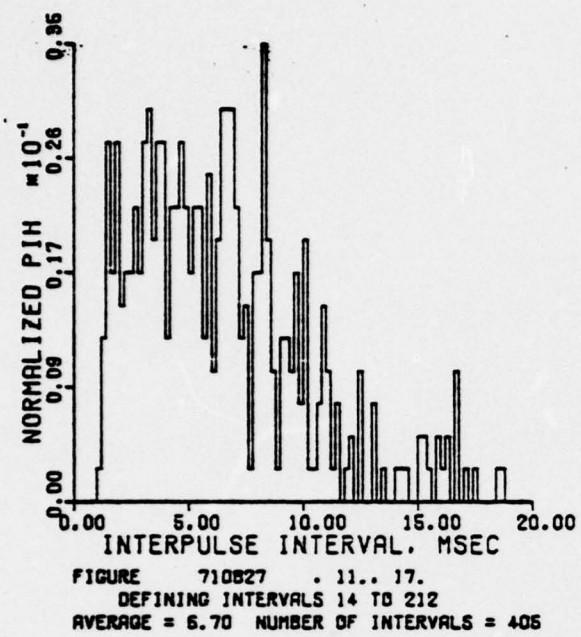
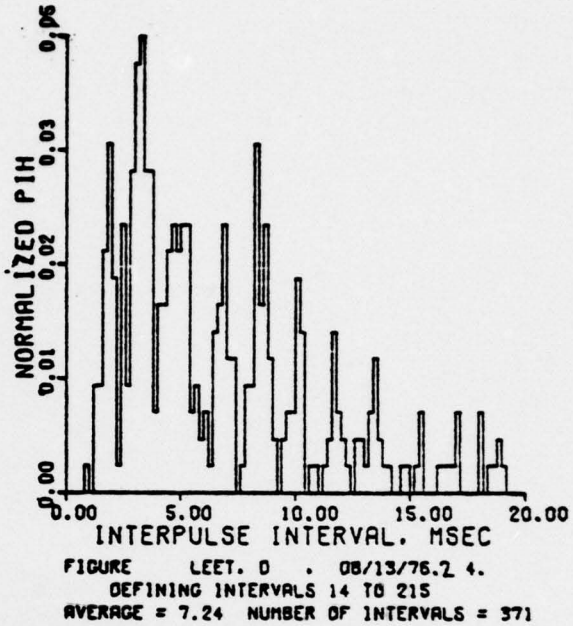
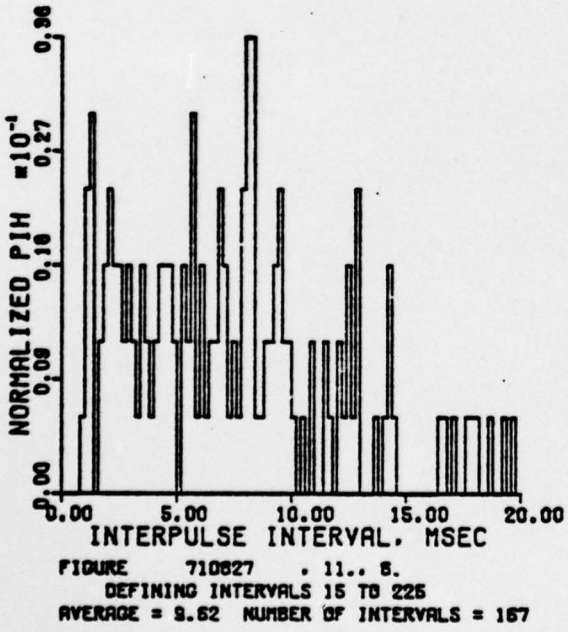


FIGURE LEET. 0 . 08/13/76.2 2.
DEFINING INTERVALS 882 TO 999
AVERAGE = 6.84 NUMBER OF INTERVALS = 164

Figure 38. /$\mathcal{E}$/-PIHs of neuron 710827/11 and Model 08/13/76 corresponding to the /$\mathcal{E}$/-POHs of Figure 35. (a) neuron run 6, (b) model run 08/13/76.1/1, (c) neuron run 15, and (d) model run 08/13/76.2/2.







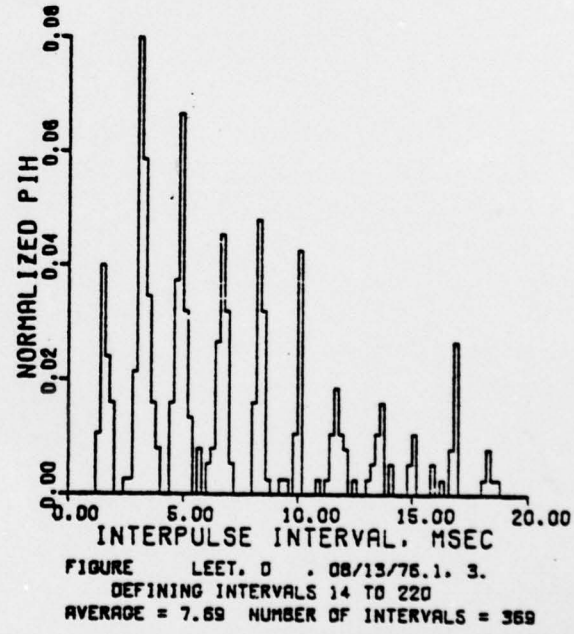


Figure 39. /$\mathcal{E}$/-PIHs of neuron 710827/11 and Model 08/13/76 corresponding to the /$\mathcal{E}$/-POHs of Figure 36. (a) neuron run 17, (b) model run 08/13/76.2/4, (c) neuron run 8, and (d) model run 08/13/76.1/3.

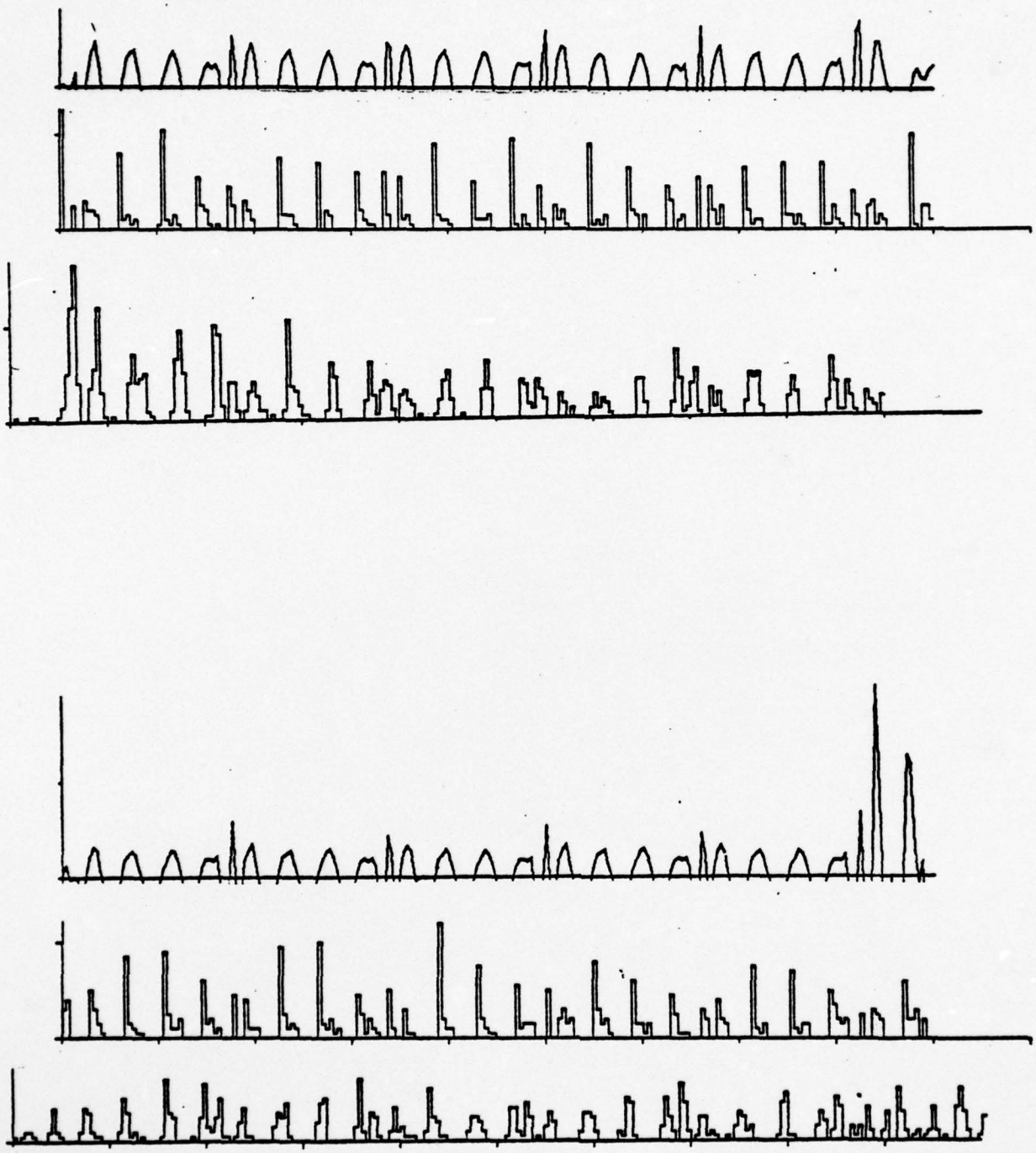


Figure 40. /I/-POHs from neuron 710827/11 (lower curve in (a) and (b)) and Model 08/13/76 (middle curve in (a) and (b)) and corresponding segment from the ROC COC2 response, positive values only (upper curve in (a) and (b)). In (a) the neuron run is 6, the model run is 08/13/76.1/1, and the stimulus is 3A, presented at an intensity of 10 dB attenuation. In (b) the neuron run is 14, the model run is 08/13/76.2/1, and the stimulus is 7A, presented at an intensity of 10 dB attenuation.

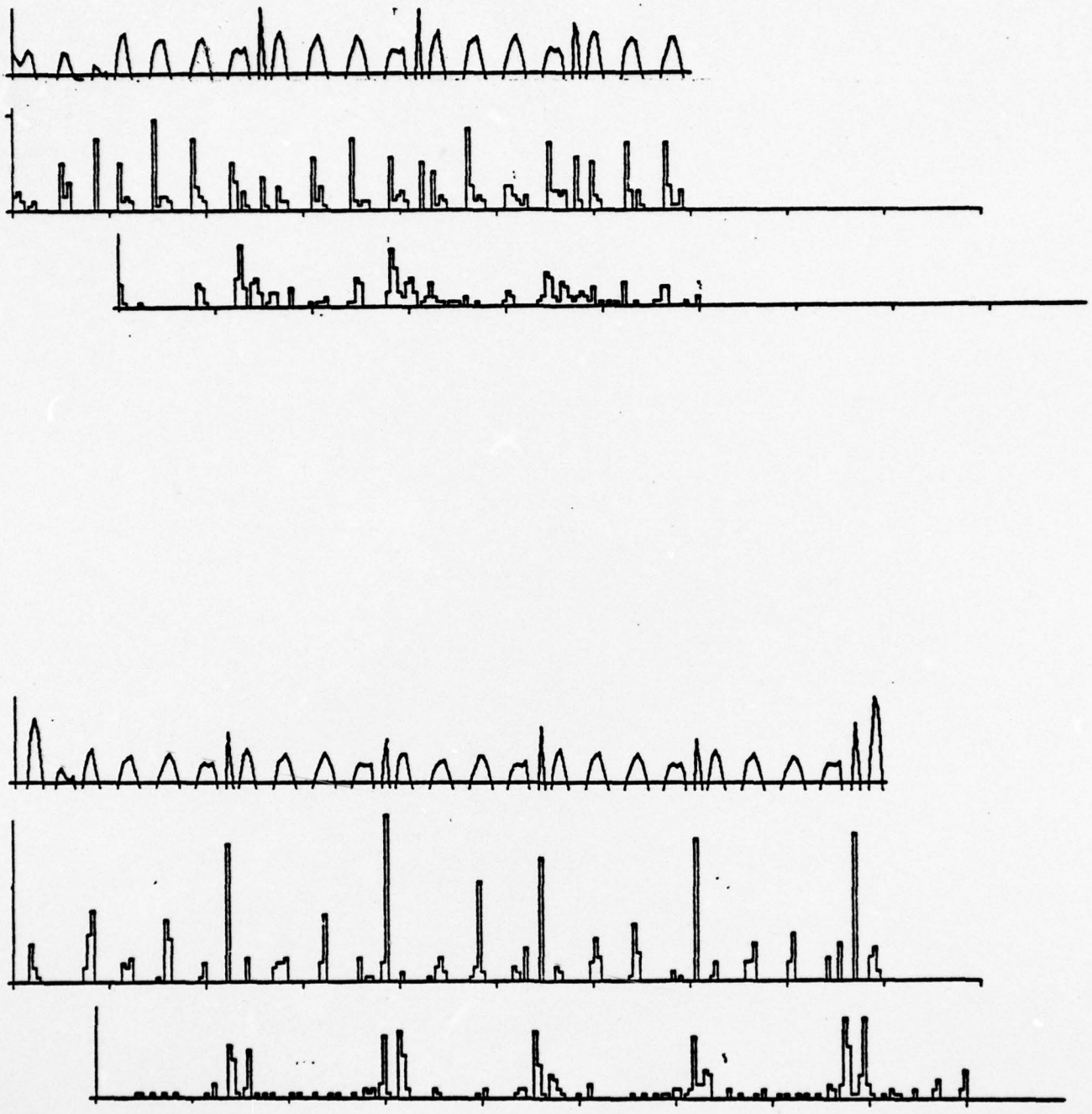


Figure 41. /I/-POHs from neuron 710827/11 (lower curve in (a) and (b)) and Model 08/13/76 (middle curve in (a) and (b)) and corresponding segment from the ROC COC2 response, positive values only (upper curve in (a) and (b)). In (a) the neuron run is 17, the model run is 08/13/76.2/4, and the stimulus is 8B, presented at an intensity of 20 dB attenuation. In (b) the neuron run is 9, the model run is 08/13/76.1/4, and the stimulus is 4B, presented at an intensity of 40 dB attenuation.

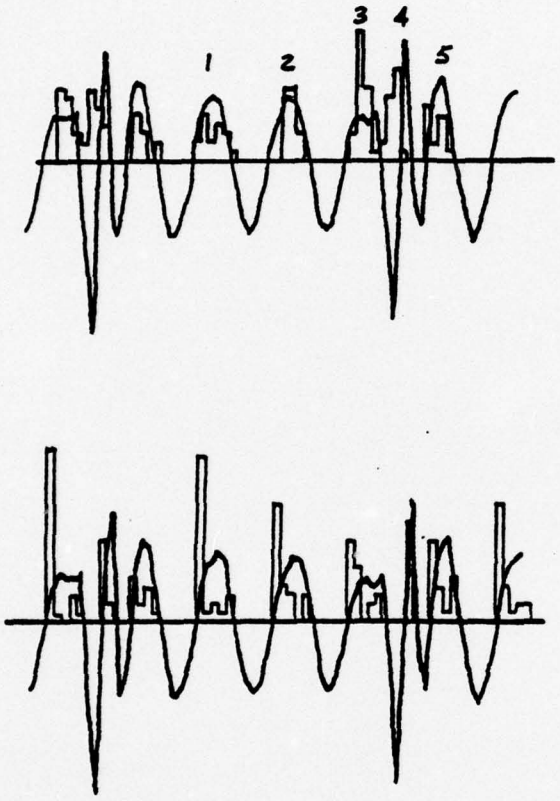


Figure 42. A pitch period of the vowel /I/ superimposed on a typical corresponding segment of a 10 dB /I/-POH. (a) is neuron 710827/11, Run 6, (b) is model run 08/13/76.1/1.

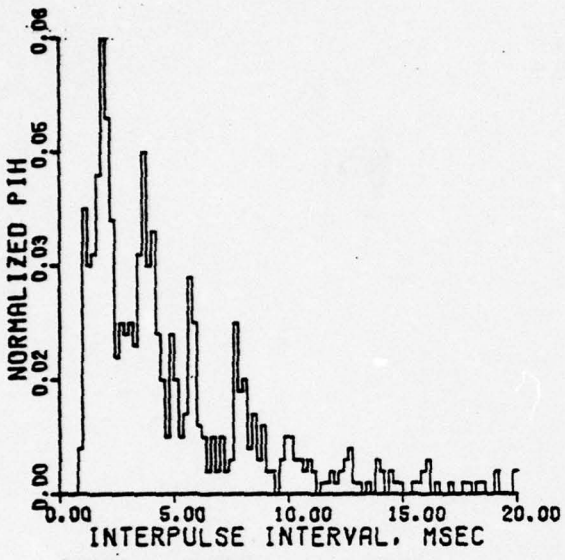


FIGURE 710827 . 11.. 6.
DEFINING INTERVALS 14 TO 215
AVERAGE = 5.06 NUMBER OF INTERVALS = 617

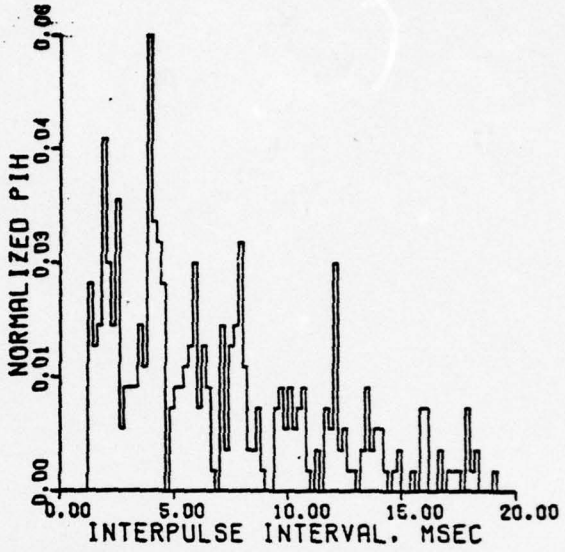


FIGURE LEET. D . 08/13/75.1. 1.
DEFINING INTERVALS 14 TO 210
AVERAGE = 7.37 NUMBER OF INTERVALS = 382

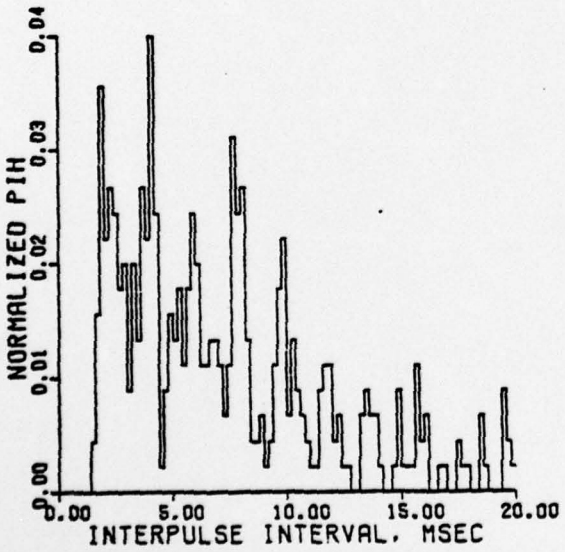


FIGURE 710827 . 11.. 14.
DEFINING INTERVALS 238 TO 458
AVERAGE = 7.58 NUMBER OF INTERVALS = 413

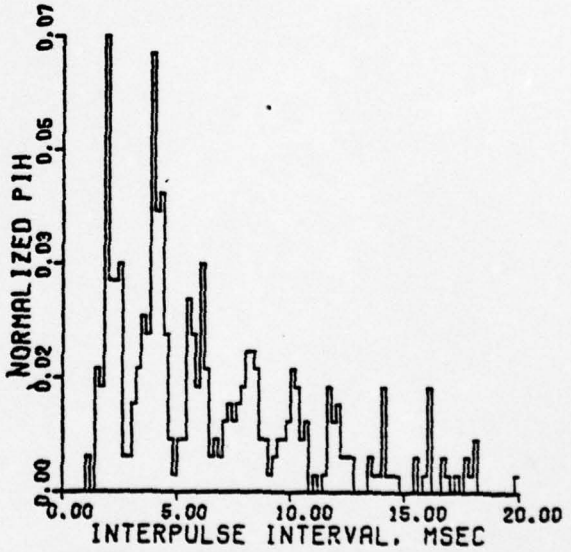
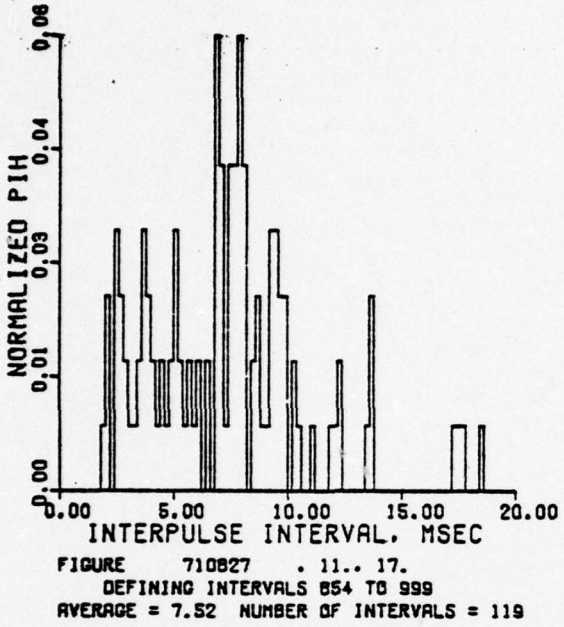
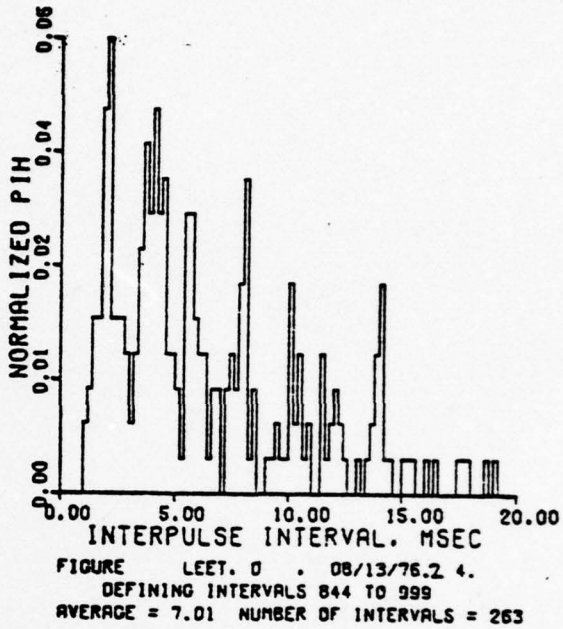
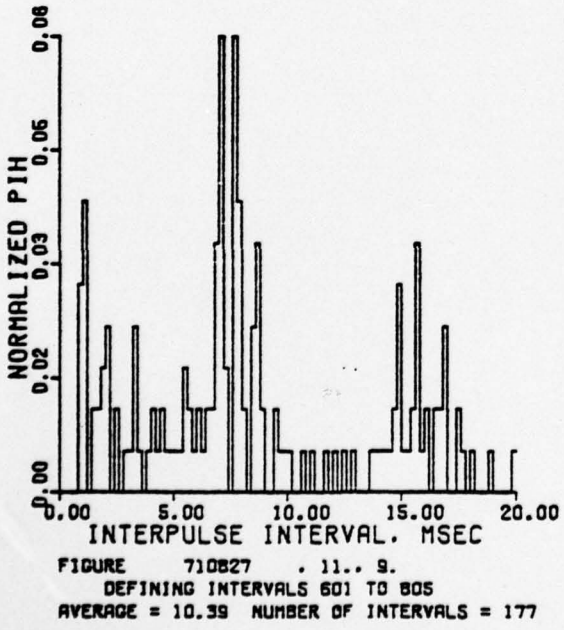


FIGURE LEET. D . 08/13/76.2 1.
DEFINING INTERVALS 228 TO 427
AVERAGE = 6.94 NUMBER OF INTERVALS = 395

Figure 43. /I/-PIHs of neuron 710827/11 and Model 08/13/76 corresponding to the /I/-POHs of Figure 40. (a) neuron run 6, (b) model run 08/13/76.1/1, (c) neuron run 14, and (d) model run 08/13/76.2/1.







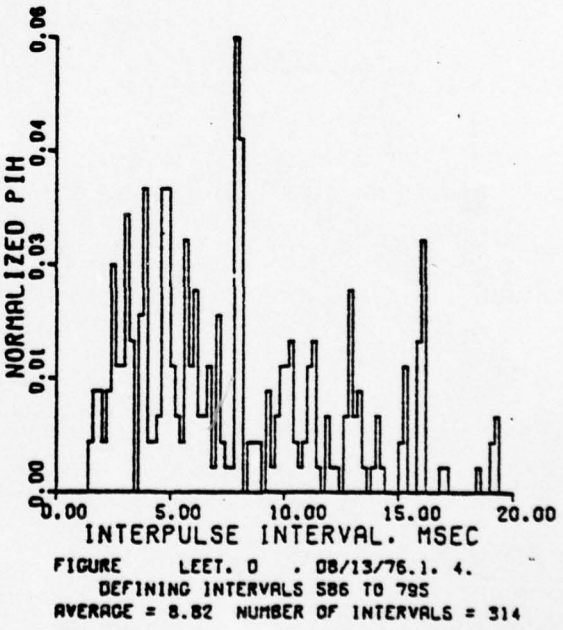


Figure 44. /I/-PIHs of neuron 710827/11 and Model 08/13/76 corresponding to the /I/-POHs of Figure 41. (a) neuron run 17, (b) model run 08/13/76.2/4, (c) neuron run 9, and (d) model run 08/13/76.1/4.

TABLE 19

PEAK OCCURRENCE TABLE - VOWEL /I/

Interpulse Interval	710827/11 Run 6	08/13/76.1 Run 1	710827/11 Run 14	08/13/76.2 Run 1	710827/11 Run 17	08/13/76.2 Run 4	710827/11 Run 9	08/13/76.1 Run 4
1.2	.079			.005			.068	
1.4		.045						
1.6				.003				
1.8								
2.0	.164	.094	.080	.111				.032
2.2					.034	.110	.040	
2.4			.080					
2.6		.065		.068	.059		.011	.057
2.8	.066							
3.0			.051					
3.2	.068							.070
3.4			.046				.034	
3.6		.050		.066				
3.8	.115		.068		.076	.095		
4.0		.107		.127				.067
4.2	.092		.094			.103	.023	
4.4				.106				
4.6					.034	.080	.023	
4.8								.086
5.0	.047		.041					
5.2					.067			
5.4			.046					
5.6				.058			.034	
5.8	.066				.034	.080		.054
6.0		.058	.068					
6.2				.066	.025		.023	.051
6.4		.042						
6.6					.017			
6.8	.015			.018		.027		.029
7.0			.041	.101				

No. Sample Intervals	202	197	221	200	147	156	205	210
Average	5.06	7.37	7.59	6.94	7.52	7.01	10.39	8.82
Number Intervals	617	382	413	395	119	263	177	314
Vowel Location	3A(1)	3A(1)	7A(2)	7A(2)	8B(5)	8B(5)	4B(4)	4B(4)
Intensity	10	10	10	10	20	20	40	40

AD-A041 882 DAYTON UNIV OHIO RESEARCH INST F/G 17/2
REVISED MODEL OF THE PERIPHERAL AUDITORY SYSTEM THROUGH PRIMARY--ETC(U)
JUN 77 D G LEET F33615-76-C-0510
UNCLASSIFIED UDRI-TR-76-86 AMRL-TR-77-35 NL

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1.0
4.5
5.0
5.6
6.3
2.8
3.2
3.6
4.0
2.5
2.2
2.0
1.8
1.1
1.25
1.4
1.6
MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

TABLE 20

STIMULUS INTERVALS TABLE
VOWEL /I/

INTERVAL	STIMULUS			
	3A	7A	8B	4B
.2	0	0	0	0
.4	0	0	0	0
.6	1	2	1	2
.8	4	2	2	0
1.0	0	0	0	0
1.2	0	0	1	0
1.4	2	0	1	0
1.6	3	4	2	0
1.8	4	5	4	0
2.0	11	9	6	0
2.2	3	2	3	0
2.4	2	4	2	0
2.6	4	2	2	0
2.8	0	0	0	0
3.0	0	0	1	0
3.2	0	0	0	0
3.4	2	0	1	0
3.6	3	4	2	0
3.8	4	5	3	0
4.0	8	6	5	0
4.2	5	4	4	0
4.4	2	4	1	0
4.6	4	2	3	0
4.8	0	0	0	0
5.0	0	0	1	0
5.2	0	0	0	0
5.4	2	0	0	0
5.6	3	4	3	0
5.8	4	4	2	0
6.0	5	4	4	0
6.2	7	6	4	0
6.4	2	4	2	0
6.6	4	1	2	0
6.8	0	0	0	0
7.0	0	0	1	0
7.2	2	0	0	0
7.4	2	4	3	1
7.6	1	0	0	0
7.8	0	0	0	0
8.0	11	10	5	2

3.11 THE VOWEL /u/

The neuron/u/-POHs are aligned with their corresponding model /u/-POHs and ROC COC2 response segments in Figures 45 and 46.

In Figure 47 about one pitch period of a ROC COC2 response is superimposed on typical corresponding segments of the neuron and model /u/-POH. It is easily seen that, in addition to firing on the prominent peaks of the ROC COC2 waveform, the neuron also fires at a point of inflection (2 in Figure 47a), on a small peak whose magnitude remains below zero (5), and on two small positive magnitude peaks (7 and 8). The model, on the other hand, fires only on peak 8, and then only in the 10 and 20 dB runs.

Since the peaks in the 10 dB /u/-POHs are about 1 msec apart and there is no 1 msec interval peak in the neuron /u/-PIH, it is probable that the neuron skips its first opportunity to fire after producing a pulse; it fires on any subsequent opportunity.

3.12 THE VOWEL /i/

The neuron and model /i/-POHs and corresponding ROC COC2 response segments are aligned in Figures 50 and 51.

In Figure 52 about a pitch period of the ROC COC2 response is superimposed on typical corresponding segments of neuron and model /i/-POHs. It can be seen that both the neuron and model fire at approximately the same points in time with respect to the pitch period peaks (see below). Model peaks are, however, much sharper. Furthermore, as can be seen from the "number of pulse intervals" row in the Peak Occurrence Table, Table 23, there are, on the average, more pulses per peak in the Model's /i/-POHs.

There is considerable variability between the two neuron 10 dB /i/-PIHs: there are five peaks that match in location but, between the two histograms, there are four peaks that do not match. The peak in the Model /i/-PIH that is consistently not matched by a peak in the neuron /i/-PIH is at 4.6-4.8 msec.

This is the interval between peaks 1 and 5 in Figure 52b. In the neuron /i/-POH the interval between peaks of activity corresponding to peaks 1 and 5 measures 5.4-5.6 msec, and the neuron /i/-PIHs have peaks corresponding to this interval.

Text continued on page 107

TABLE 21

PEAK OCCURRENCE TABLE - VOWEL /u/

Interpulse Interval	710827/11 Run 6	08/13/76.1 Run 1	710827/11 Run 14	08/13/76.2 Run 1	710827/11 Run 17	08/13/76.2 Run 4	710827/11 Run 9	08/13/76.1 Run 4
1.0		.006		.013				
1.2							.083	
1.4	.052							
1.6		.022				.010		
1.8			.064	.046			.083	
2.0	.079							.049
2.2					.061	.102	.083	
2.4	.079		.036					
2.6		.111		.105		.099		
2.8	.070						.060	
3.0				.069	.056	.048		.068
3.2							.048	
3.4								.008
3.6	.061		.060		.041			
3.8							.065	
4.0								
4.2	.076	.105		.085	.066			
4.4								
4.6		.108		.111		.147		
4.8			.108		.066			.118
5.0							.024	
5.2	.052					.083		
5.4		.044	.056				.018	.015
5.6				.043		.026		
5.8					.041		.030	
6.0	.044	.010						
6.2			.064		.046		.054	
6.4	.035	.048		.007		.016		.049
6.6								
6.8	.050						.042	
7.0			.044		.081			
7.2				.131		.105		

No. Sample Intervals	179	175	177	178	179	178	179	181
Average	6.61	7.23	7.84	7.10	8.75	7.58	8.37	9.14
Number Intervals	343	315	250	305	197	313	168	263
Vowel Location	3A(2)	3A(2)	7A(4)	7A(4)	8B(4)	8B(4)	4B(2)	4B(2)
Intensity	10	10	10	10	20	20	40	40

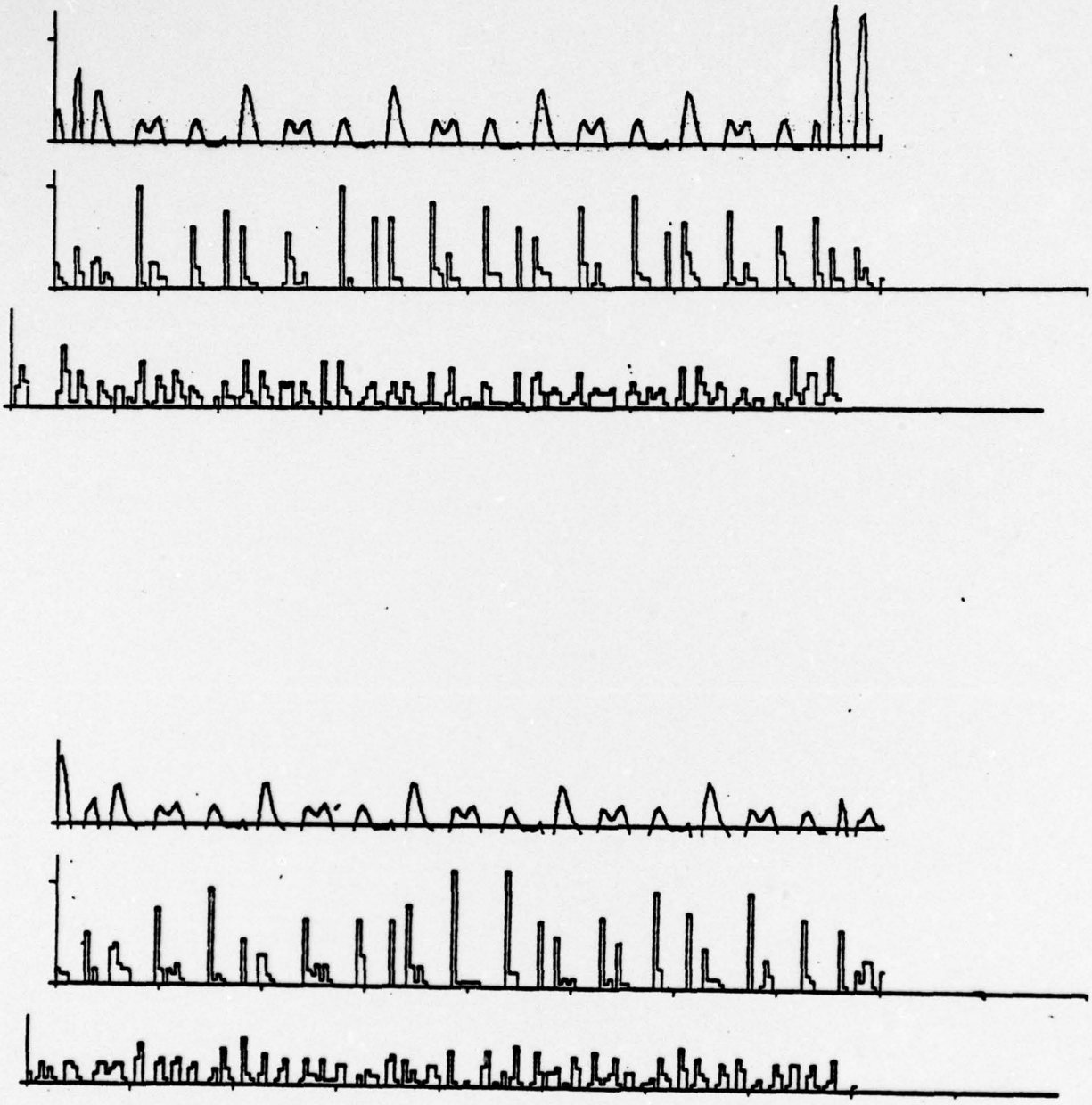


Figure 45. /u/-POHs from neuron 710827/11 (lower curve in (a) and (b)) and Model 08/13/76 (middle curve in (a) and (b)) and corresponding segment from the ROC COC2 response, positive values only (upper curve in (a) and (b)). In (a) the neuron run is 6, the model run is 08/13/76.1/1, and the stimulus is 3A, presented at an intensity of 10 dB attenuation. In (b) the neuron run is 14, the model run is 08/13/76.2/1, and the stimulus is 7A, presented at an intensity of 10 dB attenuation.

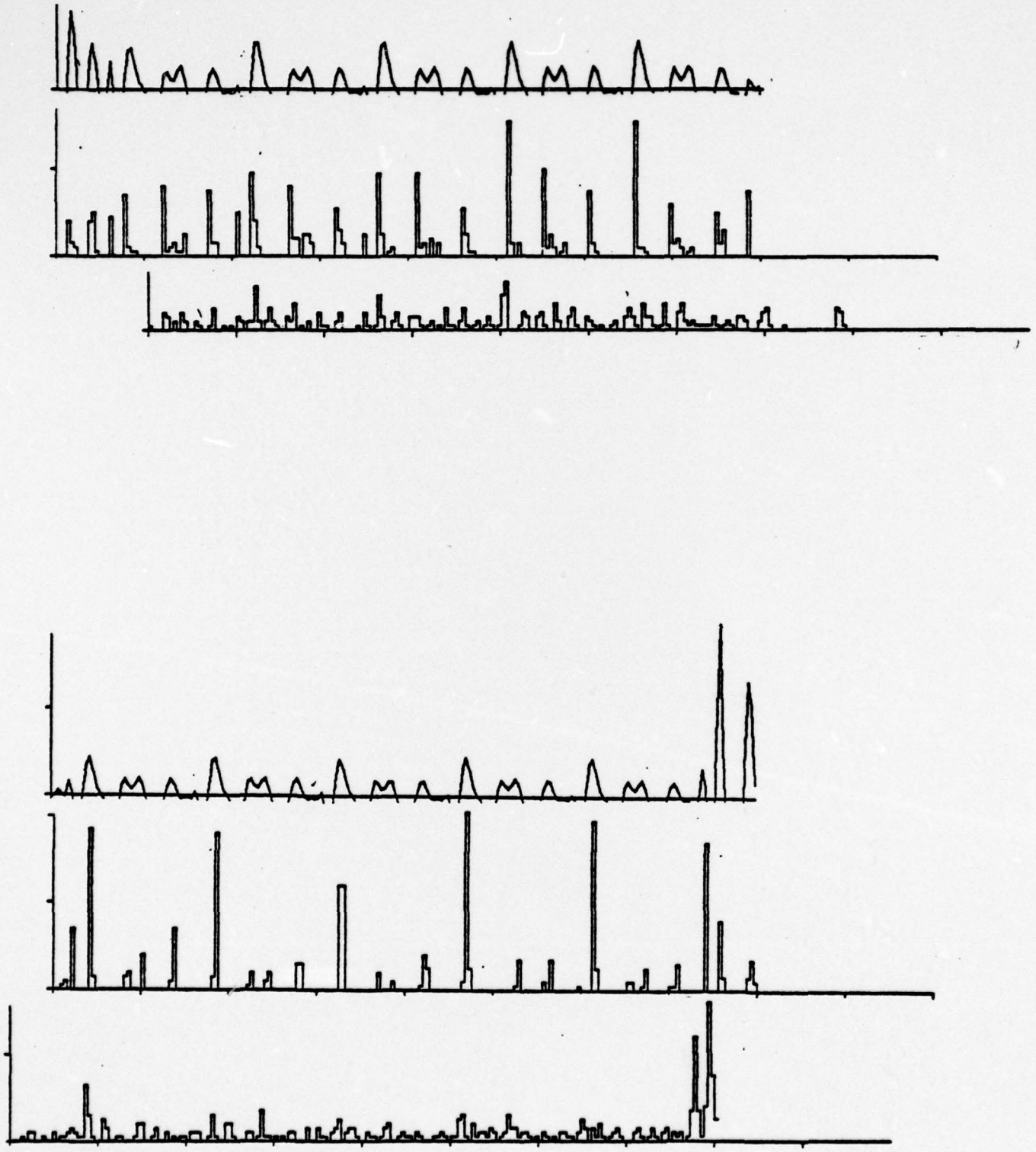


Figure 46. /u/-POHs from neuron 710827/11 (lower curve in (a) and (b)) and Model 08/13/76 (middle curve in (a) and (b)) and corresponding segment from the ROC COC2 response, positive values only (upper curve in (a) and (b)). In (a) the neuron run is 17, the model run is 08/13/76.2/4, and the stimulus is 8B, presented at an intensity of 20 dB attenuation. In (b) the neuron run is 9, the model run is 08/13/76.1/4, and the stimulus is 4B, presented at an intensity of 40 dB attenuation.

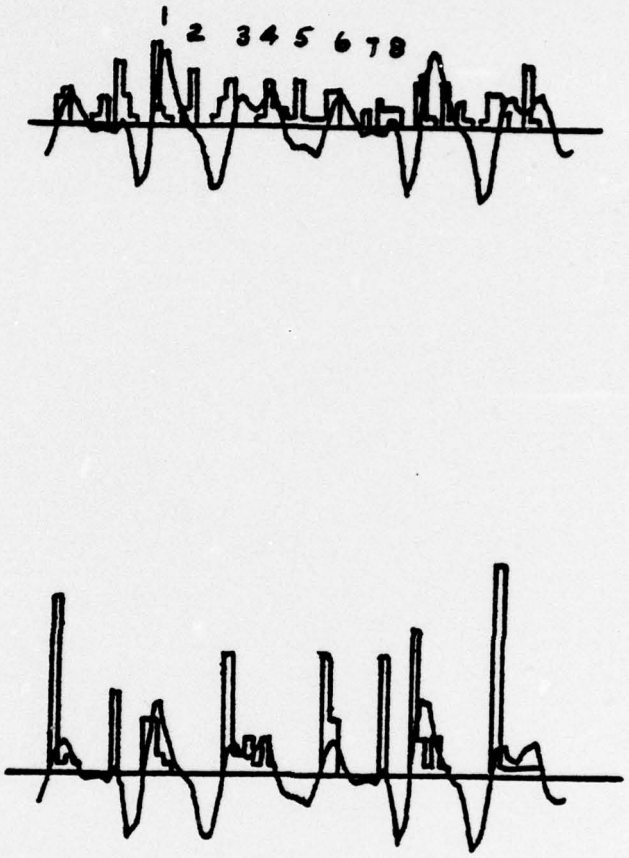
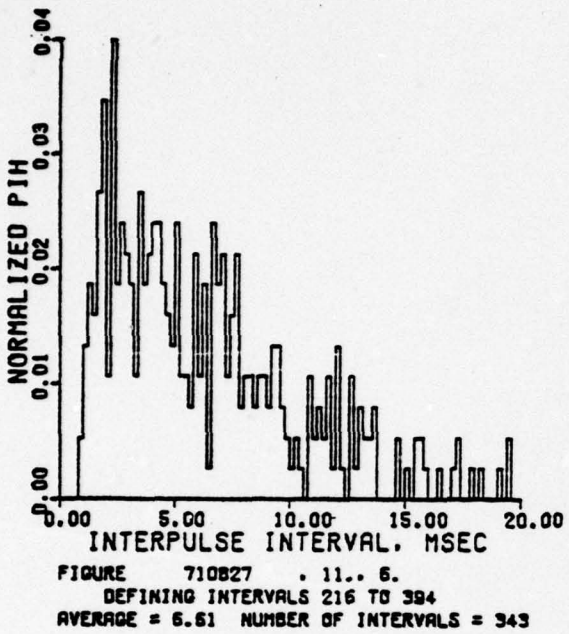
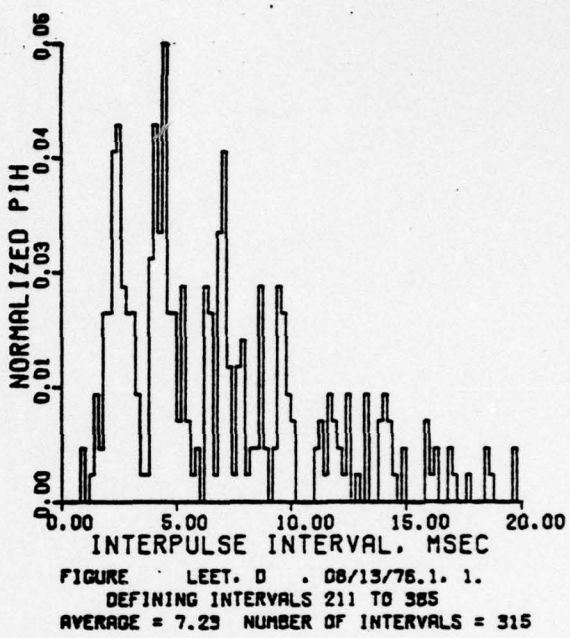
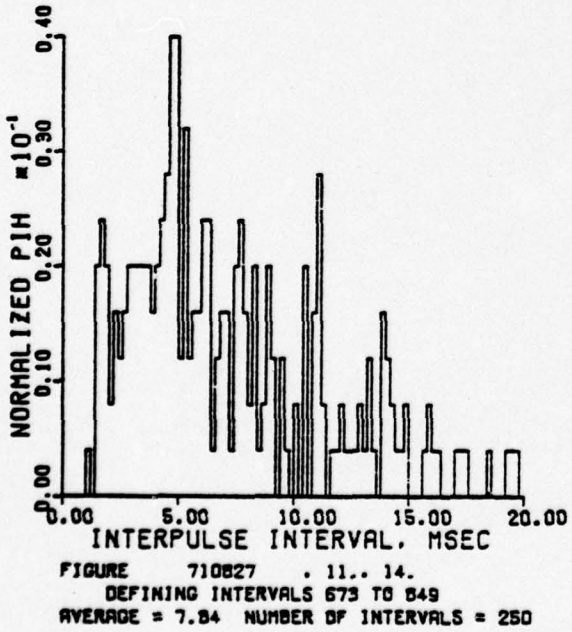


Figure 47. A pitch period of the vowel /u/ superimposed on a typical corresponding segment of a 10 dB /u/-POH. (a) is neuron 710827/11, Run 6. (b) is Model Run 08/13/76.1/1.







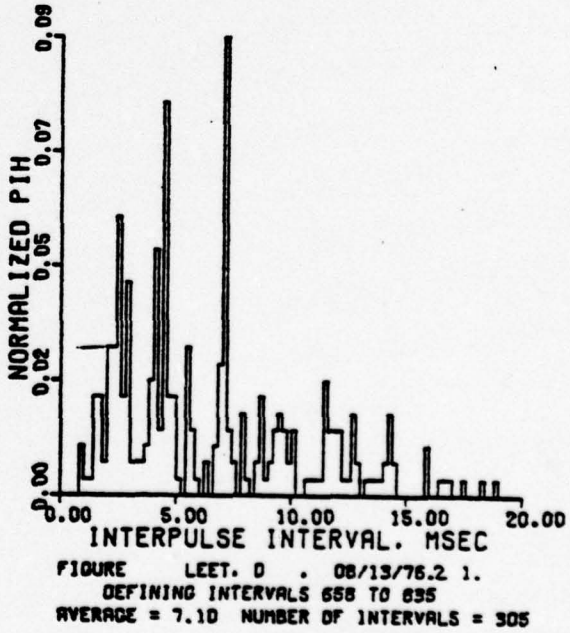
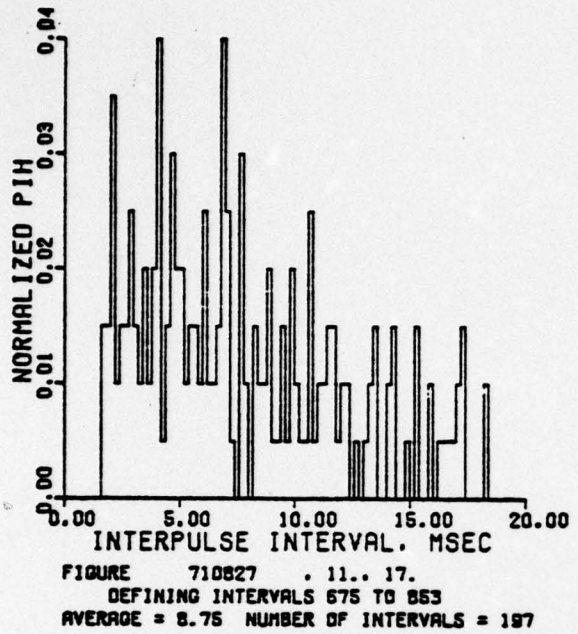
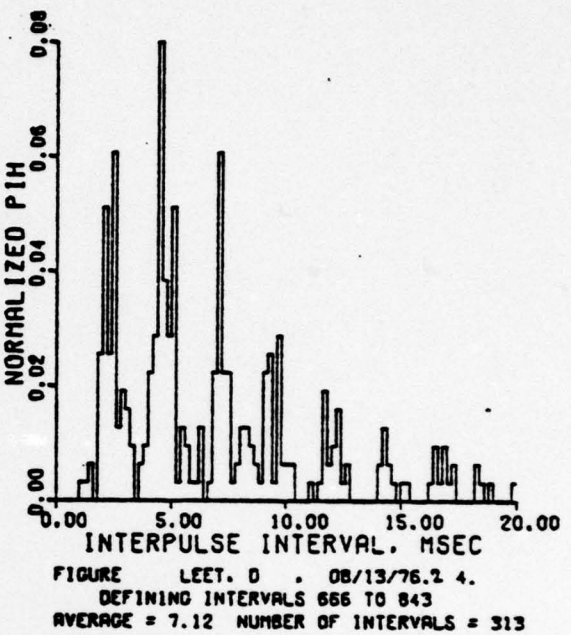
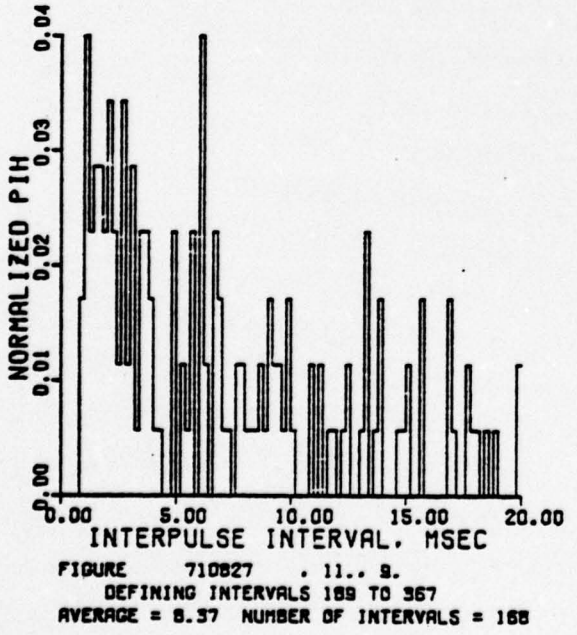


Figure 48. /u/-PIHs of neuron 710827/11 and Model 08/13/76 corresponding to the /u/-POHs of Figure 45. (a) neuron run 6, (b) model run 08/13/76.1/1, (c) neuron run 14, and (d) model run 08/13/76.2/1.







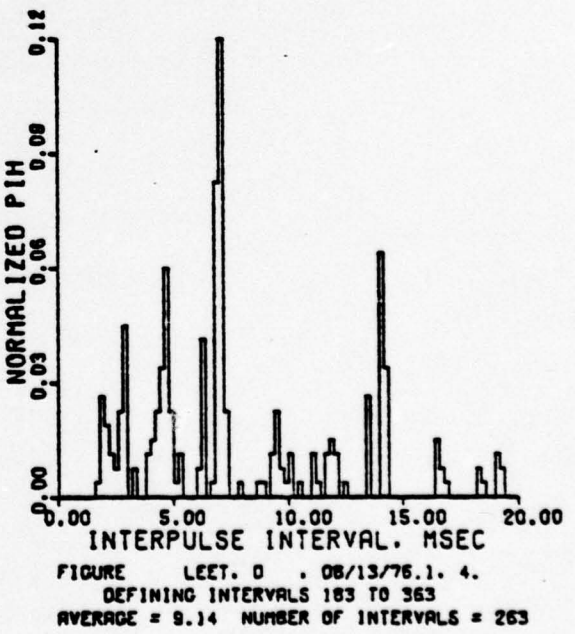


Figure 49. /u/-PIHs of neuron 710827/11 and Model 08/13/76 corresponding to the /u/-POHs of Figure 46. (a) neuron run 17, (b) model run 08/13/76.2/4, (c) neuron run 9, and (d) model run 08/13/76.1/4.

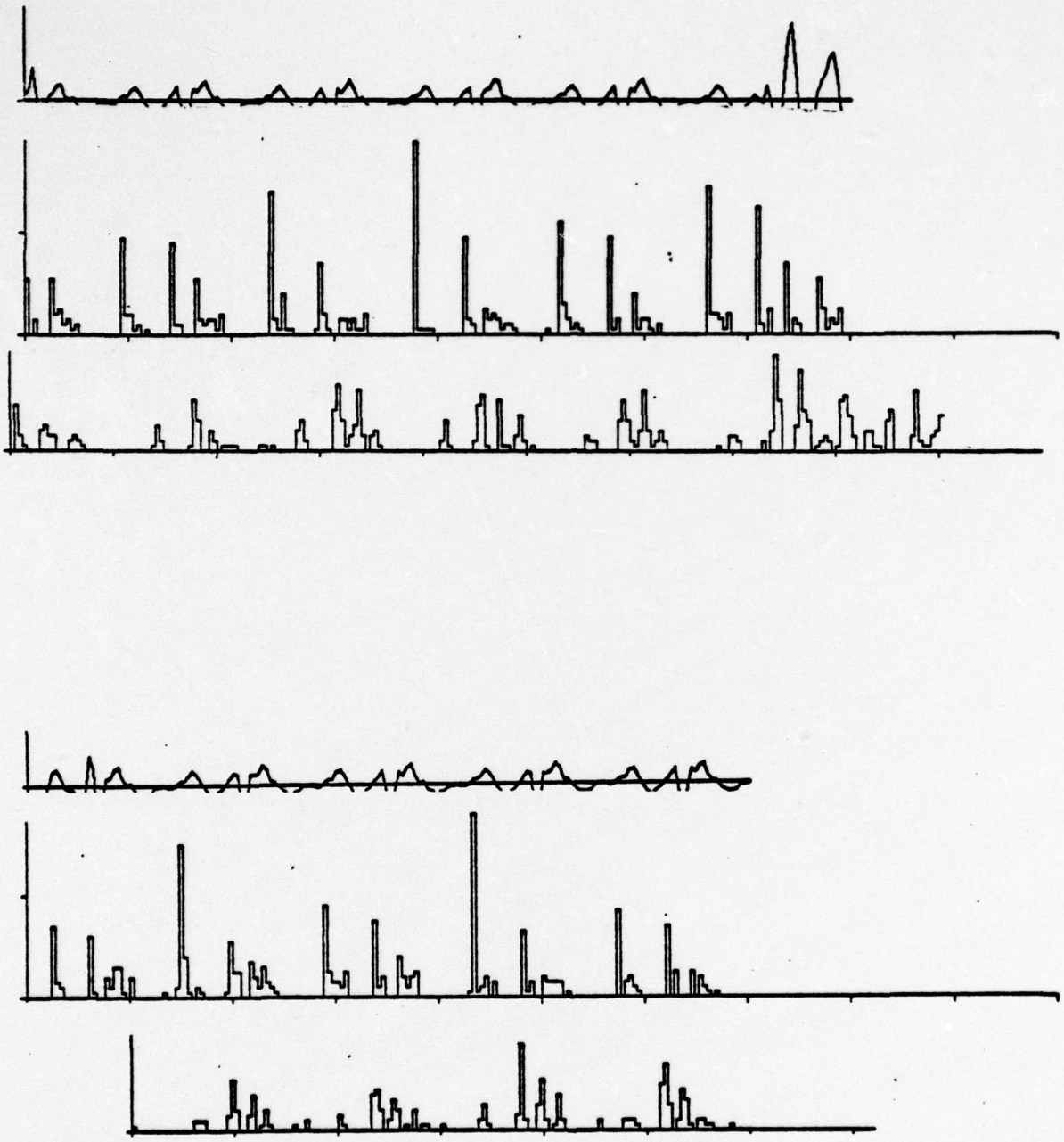


Figure 50. /i/-POHs from neuron 710827/11 (lower curve in (a) and (b)) and Model 08/13/76 (middle curve in (a) and (b)) and corresponding segment from the ROC COC2 response, positive values only (upper curve in (a) and (b)). In (a) the neuron run is 7, the model run is 08/13/76.1/2, and the stimulus is 3B, presented at an intensity of 10 dB attenuation. In (b) the neuron run is 14, the model run is 08/13/76.2/1, and the stimulus is 7A, presented at an intensity of 10 dB attenuation.

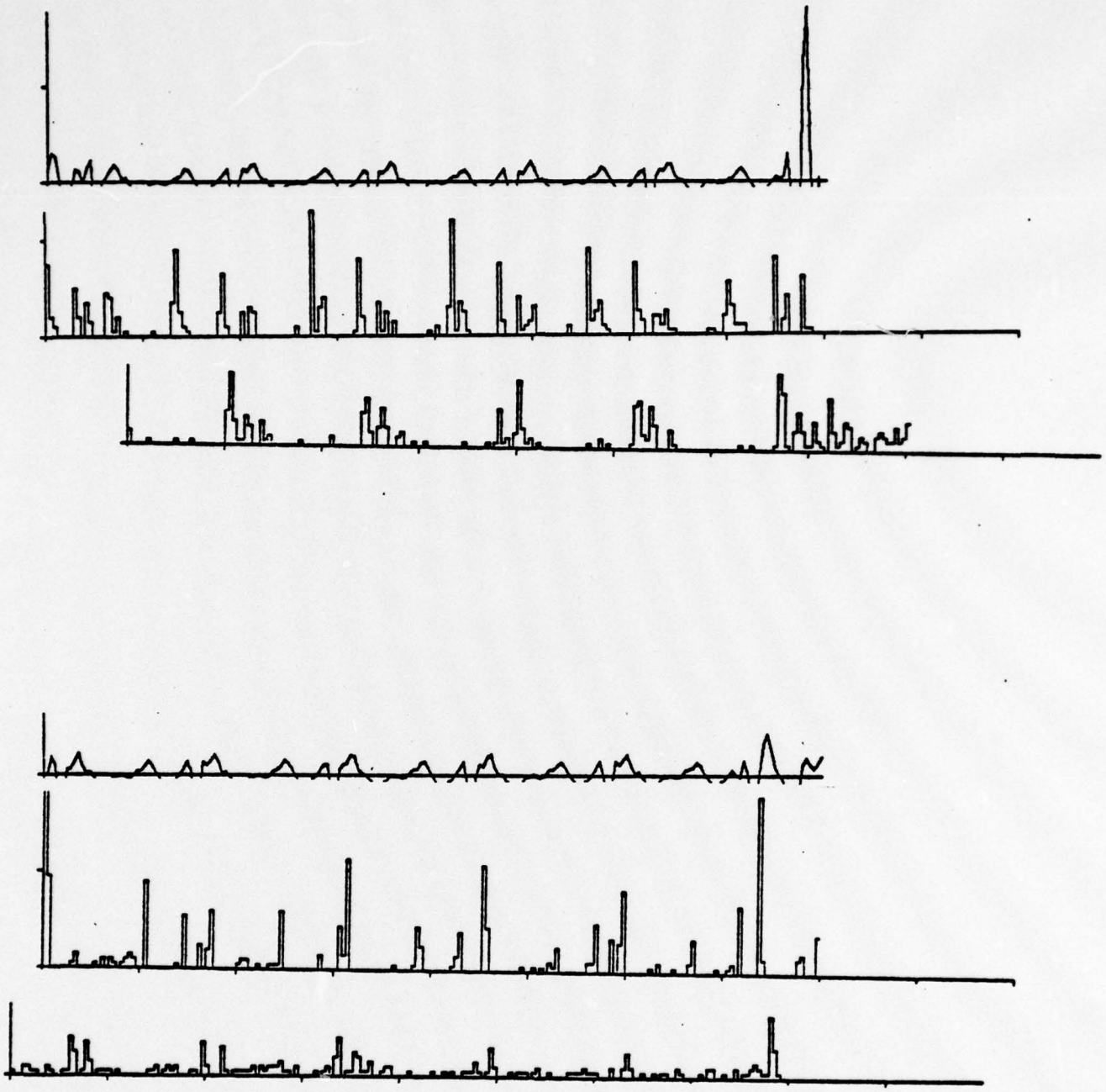


Figure 51. /i/-POHs from neuron 710827/11 (lower curve in (a) and (b)) and Model 08/13/76 (middle curve in (a) and (b)) and corresponding segment from the ROC COC2 response, positive values only (upper curve in (a) and (b)). In (a) the neuron run is 16, the model run is 08/13/76.2/3, and the stimulus is 8A, presented at an intensity of 20 dB attenuation. In (b) the neuron run is 9, the model run is 08/13/76.1/4, and the stimulus is 4B, presented at an intensity of 40 dB attenuation.

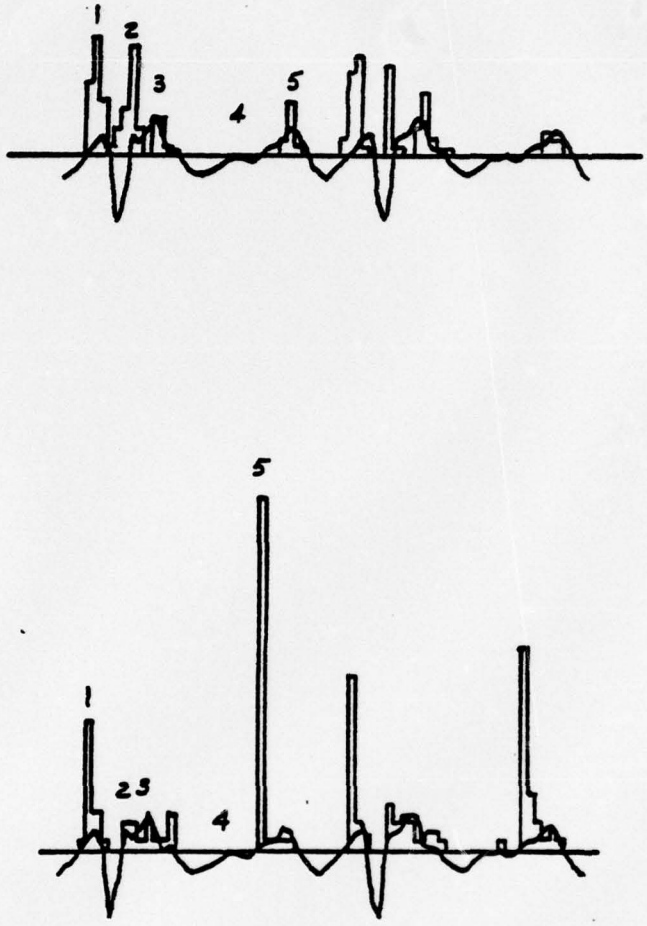


Figure 52. A pitch period of the vowel /i/ superimposed on a typical corresponding segment of a 10 dB /i/-POH. (a) is neuron 710827/11, Run 7, (b) is Model Run 08/13/76.1/2.

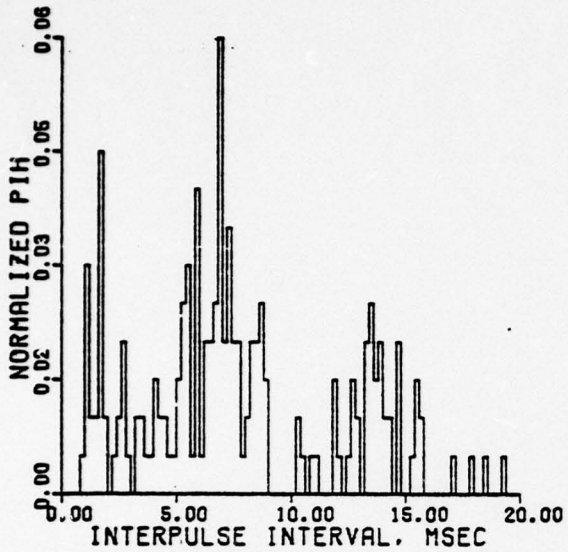


FIGURE 710827 . 11.. 7.
DEFINING INTERVALS 460 TO 640
AVERAGE = 8.46 NUMBER OF INTERVALS = 189

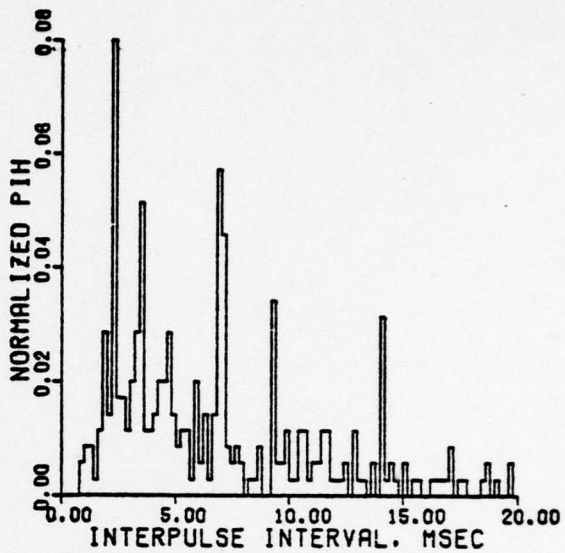


FIGURE LEET. 0 . 08/13/76.1. 2.
DEFINING INTERVALS 451 TO 632
AVERAGE = 7.21 NUMBER OF INTERVALS = 330

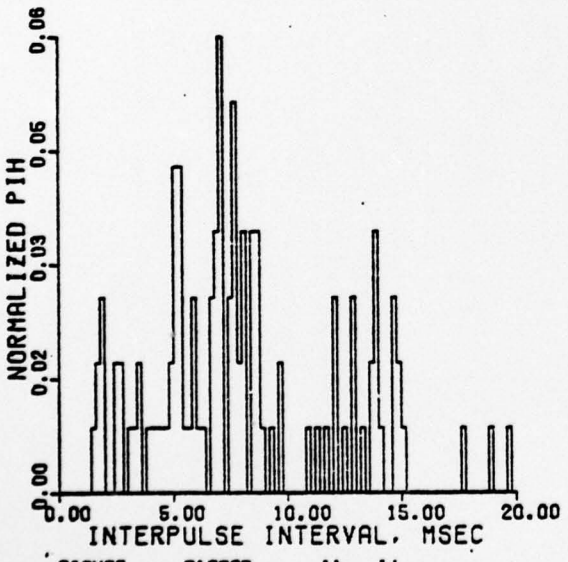


FIGURE 710827 . 11.. 14.
DEFINING INTERVALS 850 TO 999
AVERAGE = 8.78 NUMBER OF INTERVALS = 111

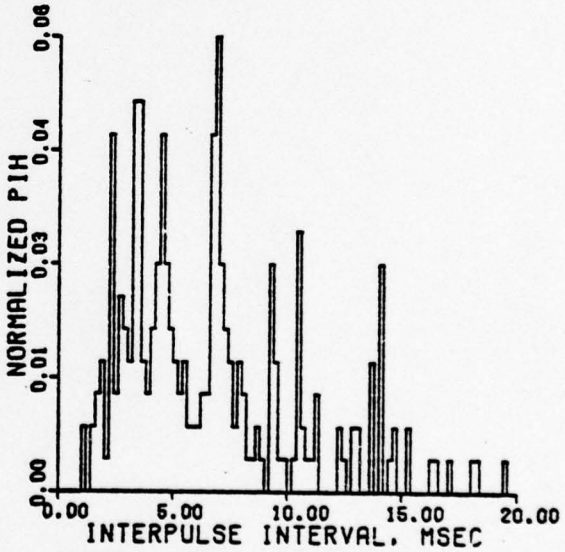


FIGURE LEET. 0 . 08/13/76.2 1.
DEFINING INTERVALS 836 TO 999
AVERAGE = 7.06 NUMBER OF INTERVALS = 248

Figure 53. /i/-PIHs of neuron 710827/11 and Model 08/13/76 corresponding to the /i/-POHs of Figure 50. (a) neuron Run 7, (b) model Run 08/13/76.1/2, (c) neuron Run 14, and (d) model Run 08/13/76.2/1.

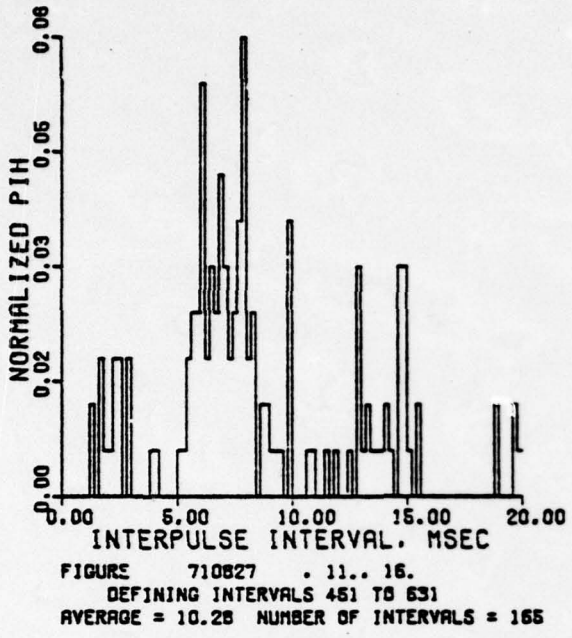


FIGURE 710827 . 11.. 16.
DEFINING INTERVALS 451 TO 631
AVERAGE = 10.28 NUMBER OF INTERVALS = 165

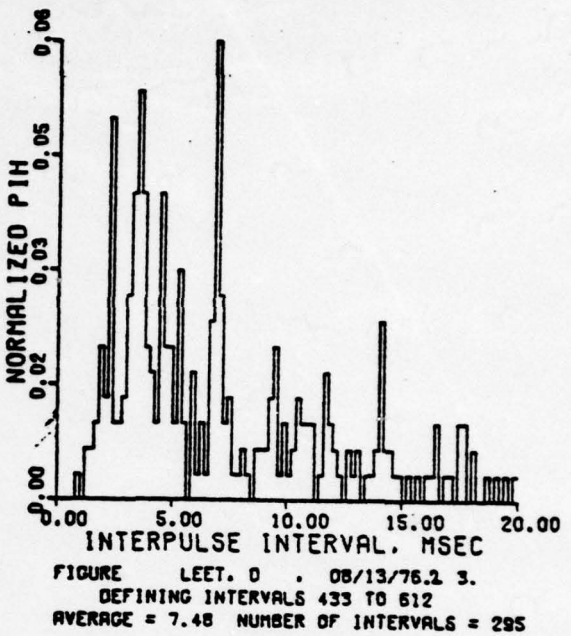


FIGURE LEET. 0 . 08/13/76.2 3.
DEFINING INTERVALS 433 TO 612
AVERAGE = 7.48 NUMBER OF INTERVALS = 295

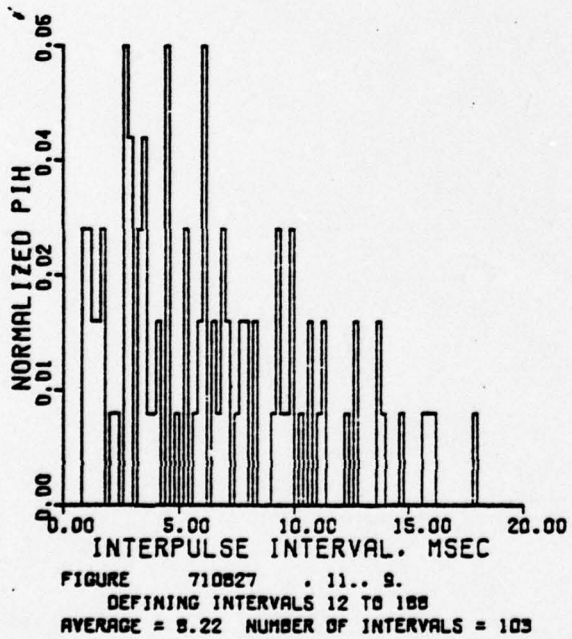


FIGURE 710827 . 11.. 9.
DEFINING INTERVALS 12 TO 188
AVERAGE = 8.22 NUMBER OF INTERVALS = 103

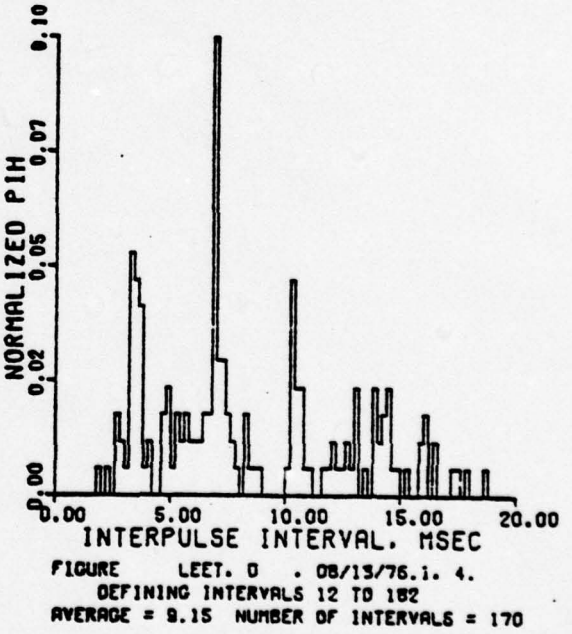


FIGURE LEET. 0 . 08/13/76.1. 4.
DEFINING INTERVALS 12 TO 182
AVERAGE = 8.15 NUMBER OF INTERVALS = 170

Figure 54. /i/-PIHs of neuron 710827/11 and Model 08/13/76 corresponding to the /i/-POHs of Figure 51. (a) neuron Run 16, (b) model Run 08/13/76.2/3, (c) neuron Run 9, and (d) model Run 08/13/76.1/4.

TABLE 22

STIMULUS INTERVALS TABLE
VOWEL /u/

INTERVAL	STIMULUS			
	3A	7A	8B	4B
.2	0	0	0	0
.4	0	0	1	0
.6	0	1	3	0
.8	3	4	4	0
1.0	1	0	3	0
1.2	0	1	2	0
1.4	0	1	3	0
1.6	4	3	4	0
1.8	1	1	0	0
2.0	3	0	0	3
2.2	1	5	5	0
2.4	3	5	4	0
2.6	6	4	5	0
2.8	2	0	0	0
3.0	2	4	4	0
3.2	0	0	0	1
3.4	0	0	1	0
3.6	0	2	6	0
3.8	0	0	1	0
4.0	0	0	0	0
4.2	4	4	4	0
4.4	3	0	0	0
4.6	5	5	4	0
4.8	1	4	5	0
5.0	3	4	4	1
5.2	1	0	0	2
5.4	2	2	0	0
5.6	2	2	4	0
5.8	0	1	3	0
6.0	0	1	2	0
6.2	2	0	3	0
6.4	2	4	4	0
6.6	0	1	2	0
6.8	0	0	1	0
7.0	6	1	1	1
7.2	9	14	16	3
7.4	0	0	1	0
7.6	0	0	0	0
7.8	0	0	0	0
8.0	3	2	0	0

TABLE 23

PEAK OCCURRENCE TABLE - VOWEL /i/

Interpulse Interval	710827/11 Run 7	08/13/76.1 Run 2	710827/11 Run 14	08/13/76.2 Run 1	710827/11 Run 16	08/13/76.2 Run 3	710827/11 Run 9	08/13/76.1 Run 4
1.0						.003		
1.2	.048	.024		.008			.078	
1.4					.012			
1.6								
1.8	.069				.024		.049	
2.0		.058	.018	.032		.044		.006
2.2								
2.4		.118		.060	.042	.075	.020	.006
2.6			.018					
2.8	.037			.056			.087	.029
3.0					.018			
3.2								
3.4								.106
3.6	.026	.097	.009	.113		.136	.078	
3.8								
4.0					.012			
4.2	.032						.029	.018
4.4								
4.6				.101		.071	.049	
4.8		.067						
5.0							.010	.047
5.2								
5.4		.033	.054			.051	.029	.035
5.6	.064			.036				
5.8								.041
6.0	.053	.030	.018			.020		
6.2					.097		.068	
6.4	.023	.024				.017		
6.6					.073		.029	
6.8								
7.0	.111	.124		.129	.097	.112	.058	.147
7.2								

No. Sample Intervals	181	182	150	164	181	280	177	171
Average	8.46	7.21	8.78	7.06	10.28	7.48	8.22	9.15
Number Intervals	189	330	111	248	165	295	103	170
Vowel Location	3B(3)	3B(3)	7A(5)	7A(5)	8A(3)	8A(3)	4B(1)	4B(1)
Intensity	10	10	10	10	20	20	40	40

TABLE 24

STIMULUS INTERVALS TABLE
VOWEL /i/

INTERVAL	STIMULUS			
	3B	7A	8A	4B
.2	0	0	0	0
.4	0	0	0	0
.6	2	1	0	0
.8	2	2	0	0
1.0	3	2	0	0
1.2	3	4	4	4
1.4	0	0	0	0
1.6	0	0	0	0
1.8	0	0	0	0
2.0	0	0	0	0
2.2	2	0	0	0
2.4	3	4	2	2
2.6	2	3	3	3
2.8	3	1	0	0
3.0	4	1	0	0
3.2	2	1	0	0
3.4	3	5	5	5
3.6	7	6	1	1
3.8	1	2	3	3
4.0	4	1	0	0
4.2	2	2	0	0
4.4	0	1	0	0
4.6	3	3	4	4
4.8	2	2	0	0
5.0	0	0	0	0
5.2	0	0	0	0
5.4	0	0	0	0
5.6	0	0	0	0
5.8	5	2	2	2
6.0	1	2	3	3
6.2	1	2	0	0
6.4	2	1	0	0
6.6	2	1	0	0
6.8	2	1	0	0
7.0	9	5	4	4
7.2	4	6	8	8
7.4	0	1	0	0
7.6	2	0	0	0
7.8	2	2	0	0
8.0	1	2	0	0

3.13 SUMMARY

The results of this section can be summarized by classifying the vowels into one of three groups according to the following criterion: the neuron has peaks of activity in the vowel-POH corresponding to positive magnitude peaks in the channel 20 response of ROC COC2. Those vowels that satisfy this criterion have neuron and model vowel-POHs and vowel PIHs that correlate well in the position of their peaks.

The vowels that satisfy this criterion are /ɛ/, /æ/, /i/, /ɔ/, and /I/. The vowels that do not are /ə/, /a/, /o/, and /u/. For each of the latter vowels, there is at least one peak per pitch period in the vowel-POH that does not have a corresponding peak in the channel 20 response of ROC COC2.

The vowel /ɚ/ was unique in that it satisfied the criterion for stimulus intensities of 10 and 20 dB attenuation, but it did not satisfy the criterion for the 40 dB attenuation stimulus. In this case there are two peaks in the channel 20 ROC COC2 response waveform for a pitch period that do not appear to have enough magnitude.

SECTION 4
DISCUSSION

4.1 INTRODUCTION

A principle characteristic of the model is that peaks in syncoder activity occur at peaks in the response of the cochlear filter channel* that provides the stimulus. The hypothesis for the auditory system is that peaks in neural activity occur at peaks in the rarefaction displacement of that segment of the basilar membrane from which the neuron receives stimulation.

In the previous section it was shown that, for several vowel stimuli, peaks in neuron 710827/11's vowel POHs did not have corresponding peaks in the channel 20 response of ROC COC2.

If the model is basically correct, this suggests that the vowel stimuli seen by the syncoder should be modified to conform more closely to the neuron vowel-POHs. The modification will generally require an increase in the magnitude of the high frequency components to provide the increased number of peaks per pitch period seen in the neuron vowel-POHs.

Two modifications are considered here. The first involves using a different ROC COC2 channel as the stimulus. The second involves modifying the middle ear circuit.

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*To be absolutely correct, peaks in syncoder activity occur at negative peaks in the response of a cochlear filter channel. Negative values in the output space of the cochlear filter were determined in early experiments to correspond to rarefaction in the basilar membrane.

4.2 ROC COC2 RESPONSE FROM SEVERAL CHANNELS TO VOWEL SEGMENTS

The ROC COC responses from channels 20 (best frequency = 1111 Hz)*, 18 (best frequency = 1492 Hz), 16 (best frequency = 2000 Hz), and 14 (best frequency =2500H3) are juxtaposed in Figures 55-64 for each of the ten vowels. The problem posed is whether a higher frequency channel can consistently provide a better fit than channel 20 to the neuron vowel-POHs. Each of the ten figures is examined with this problem in mind.

The Vowel /ɚ/

Referring to Figure 6 and 7 neural activity peaks occur at response peaks 2 and 4 at all intensities; there are no model activity peaks at response peaks 2 and 4 at an intensity of 40 dB. This suggests that peaks 2 and 4 should have slightly more magnitude. In Figure 55 it can be seen that in all channels below channel 20 these two peaks are relatively larger, large enough, it is suspected, to produce peaks in the model /ɚ/-POHs corresponding to them.

The Vowel /ə/

Referring to Figure 12 neural activity peaks occur between response peaks 2 and 3, 3 and 4, and 4 and 5, as well as on the response peaks themselves. In Figure 56, by channel 14 a peak in the response has developed between peaks 1 and 2. Also by channel 14, a notch has developed in some of the peak 3 waveforms and a glitch in the waveform is evident between peaks 4 and 5. But none of the channels examined provides a complete correlation with the neural /ə/-POH.

*The best frequency is the frequency of minimum transfer impedance.

Text continued on page 114

Figure 55. /ɹ/ - Segments of the Responses of Four ROC COC2 Channels to the /u/ - Segment of Glot-1 Stimulus 4B. The four plots do not have the same scale.

(a) Channel 20 (best frequency = 1111 Hz)

(b) Channel 18 (best frequency = 1492 Hz)

(c) Channel 16 (best frequency = 2000 Hz)

(d) Channel 14 (best frequency = 2500 Hz)

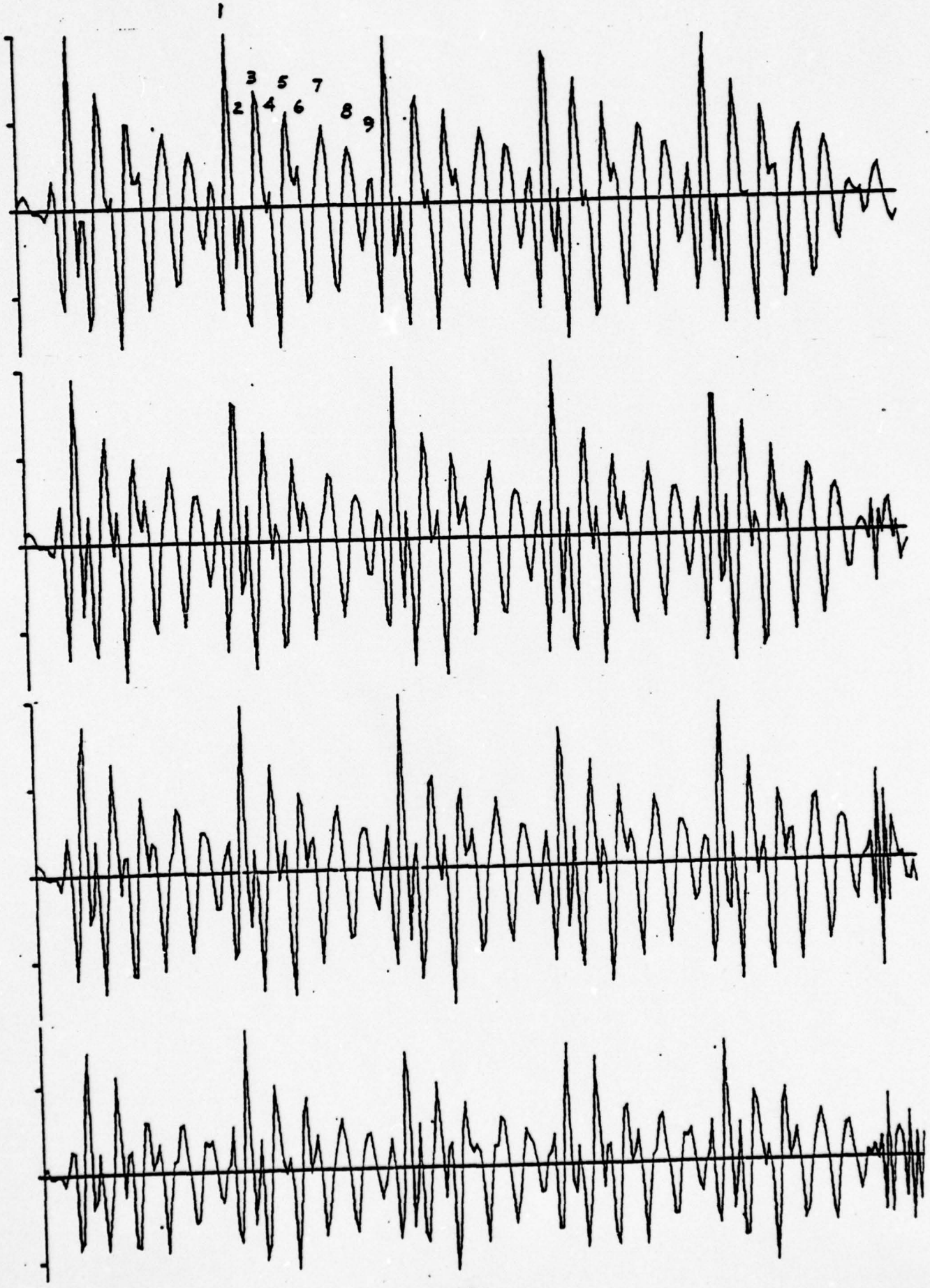

1
2
3
4
5
6
7
8
9

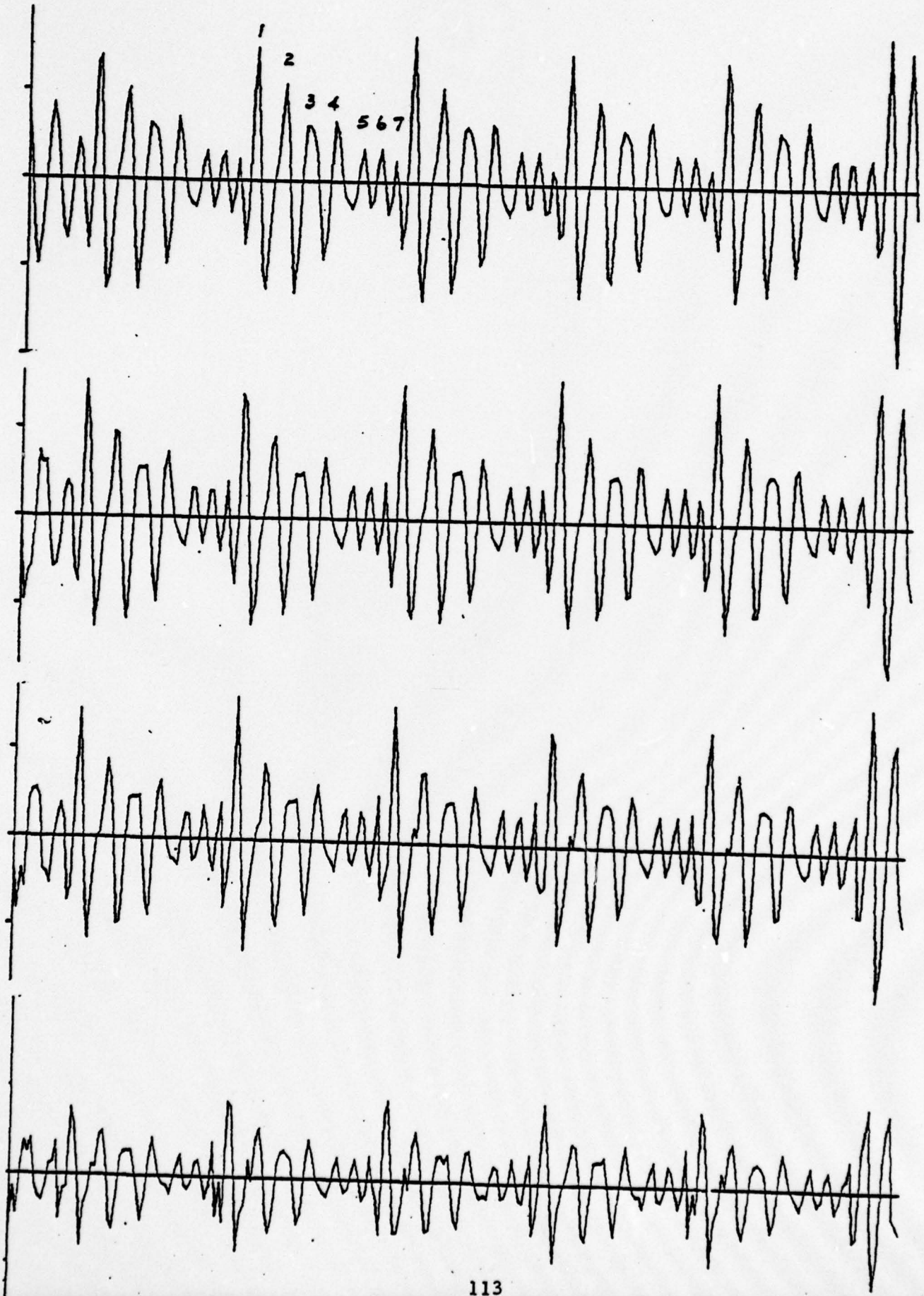
Figure 56. /ə/-Segments of the Responses of Four ROC COC2 Channels to the /ə/-Segment of Glot-1 Stimulus 4A. The four plots do not have the same scale.

(a) Channel 20 (best frequency = 1111 Hz)

(b) Channel 18 (best frequency = 1492 Hz)

(c) Channel 16 (best frequency = 2000 Hz)

(d) Channel 14 (best frequency = 2500 Hz)


1
2
3 4
5 6 7

The Vowel /a/

The only important inconsistency in Figure 17 between neural and model /a/-POHs was the neuron's consistently stronger response to peak 8 of the channel 20 response waveform. This suggested that the peak 8 seen by the neuron might be relatively larger than the channel 20 response. Figure 57 reveals that the peak is relatively larger in the higher frequency channels, starting with channel 18.

The Vowel /ɔ /

Figure 22 shows a good correlation between neuron and model /ɔ/-POHs. This observation is ratified in Figure 58, where there is little difference in the waveshapes from channel 14 to channel 20.

The Vowel /æ/

In Figure 27 there is a good correlation between the neuron /æ/-POH, the model /æ/-POH and the displacement of the corresponding segment of the channel 20 response. Note in Figure 59 that by channel 18 a glitch has begun to develop on the side of peak 7. This glitch is a full-fledged peak by channel 16. Also by channel 16 a peak has developed on the side of peak 1. Theres is no evidence for these peaks in the neuron /æ/-POH. Therefore, channel 18 is the highest frequency channel consistent with the neural data.

The Vowel /o/

The principle difference in Figure 32 between neuron and model /o/-POH is the activity corresponding to the glitch labeled 4 in Figure 60. This suggests that this peak is larger in the waveform seen by the neuron. In Figure 60, peak 4 finally becomes greater than zero in channel 14, but not much greater. Furthermore, peak 6 becomes a double peak by channel 18, and there is no evidence of this double peak in the neural data. Overall, no channel in Figure 60 matches the neural data.

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Figure 57. /a/-Segments of the Responses of Four ROC COC2 Channels to the /a/-Segment of Glot-1 Stimulus 4A. The four plots do not have the same scale.

(a) Channel 20 (best frequency = 1111 Hz)

(b) Channel 18 (best frequency = 1492 Hz)

(c) Channel 16 (best frequency = 2000 Hz)

(d) Channel 14 (best frequency = 2500 Hz)

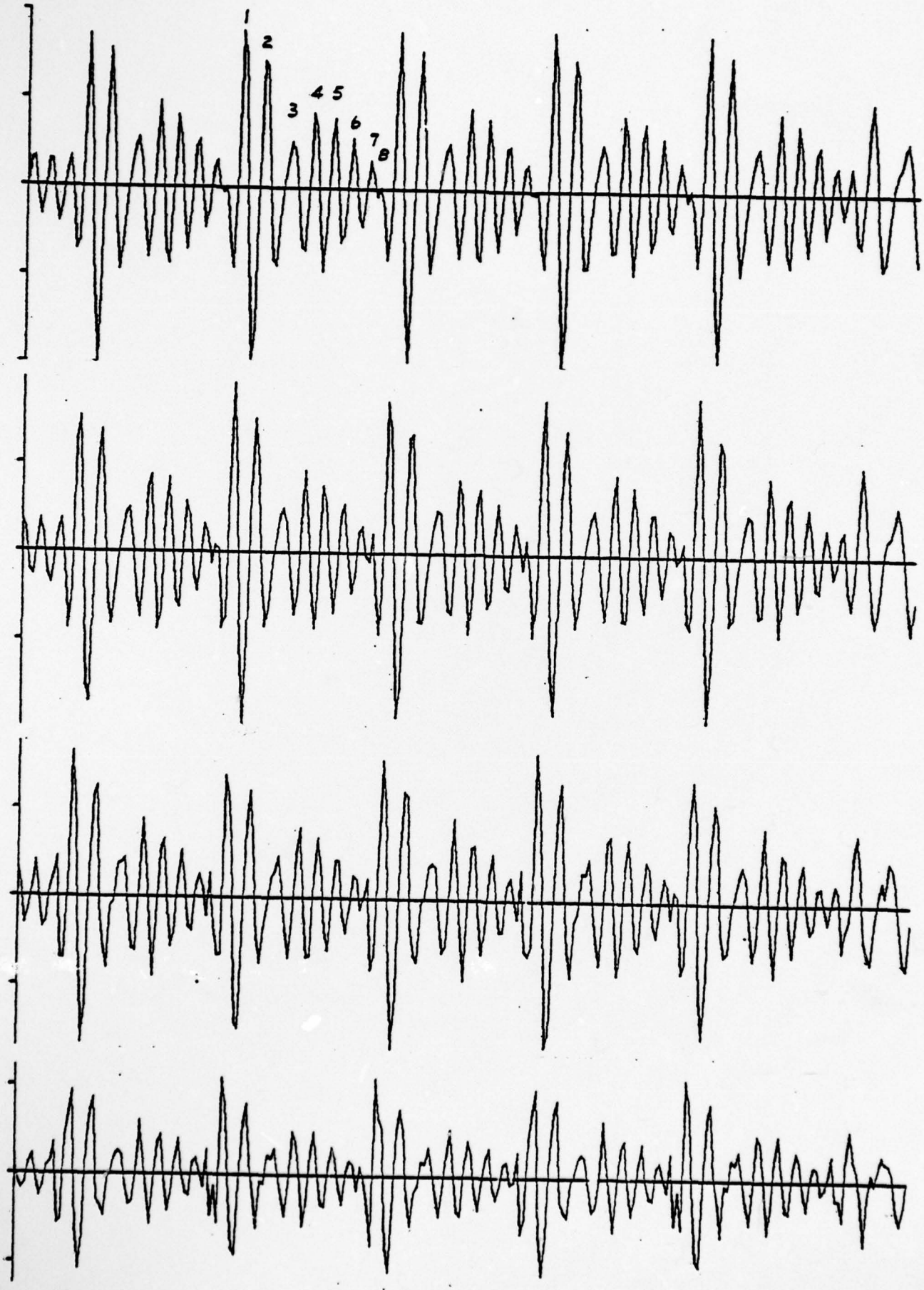

1
2
3
4 5
6
7
8

Figure 58. /ɔ/-Segments of the Responses of Four ROC COC2 Channels to the /u/-Segment of Glot-1 Stimulus 4B. The four plots do not have the same scale.

(a) Channel 20 (best frequency = 1111 Hz)

(b) Channel 18 (best frequency = 1492 Hz)

(c) Channel 16 (best frequency = 2000 Hz)

(d) Channel 14 (best frequency = 2500 Hz)

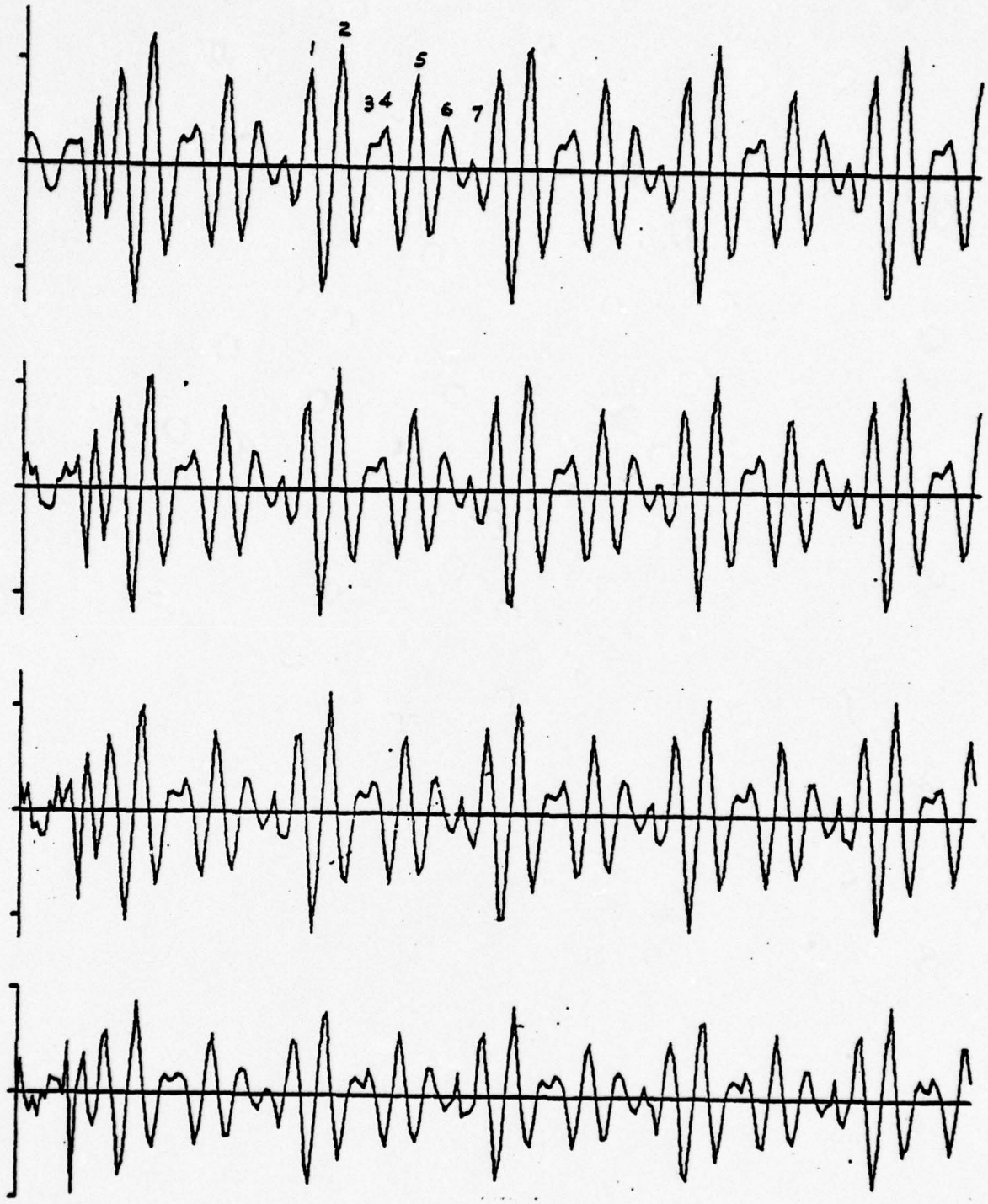

1
2
3
4
5
6
7

Figure 59. /æ/-Segments of the Responses of Four ROC COC2 Channels to the /æ/-Segment of Glot-1 Stimulus 4A. The four plots do not have the same scale.

(a) Channel 20 (best frequency = 1111 Hz)

(b) Channel 18 (best frequency = 1492 Hz)

(c) Channel 16 (best frequency = 2000 Hz)

(d) Channel 14 (best frequency = 2500 Hz)

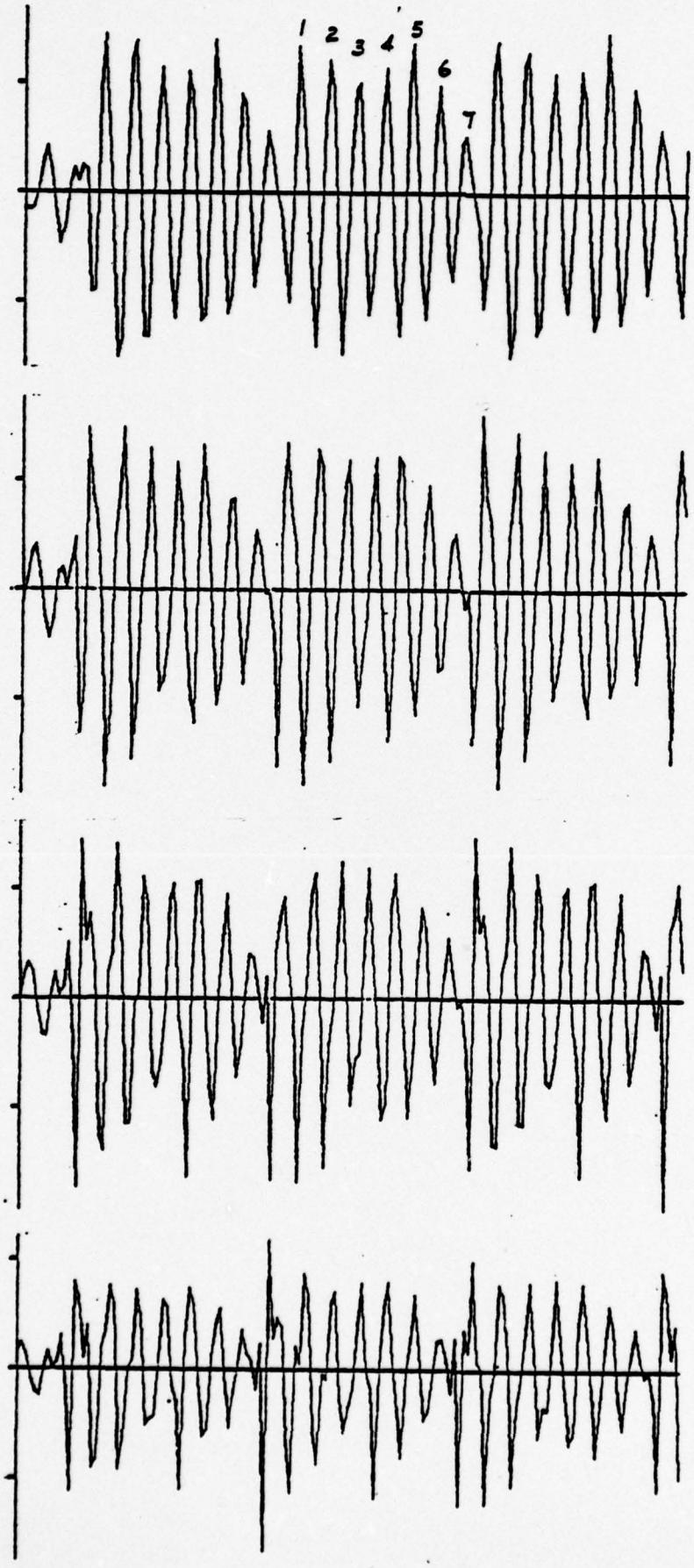

1
2
3
4
5
6
7

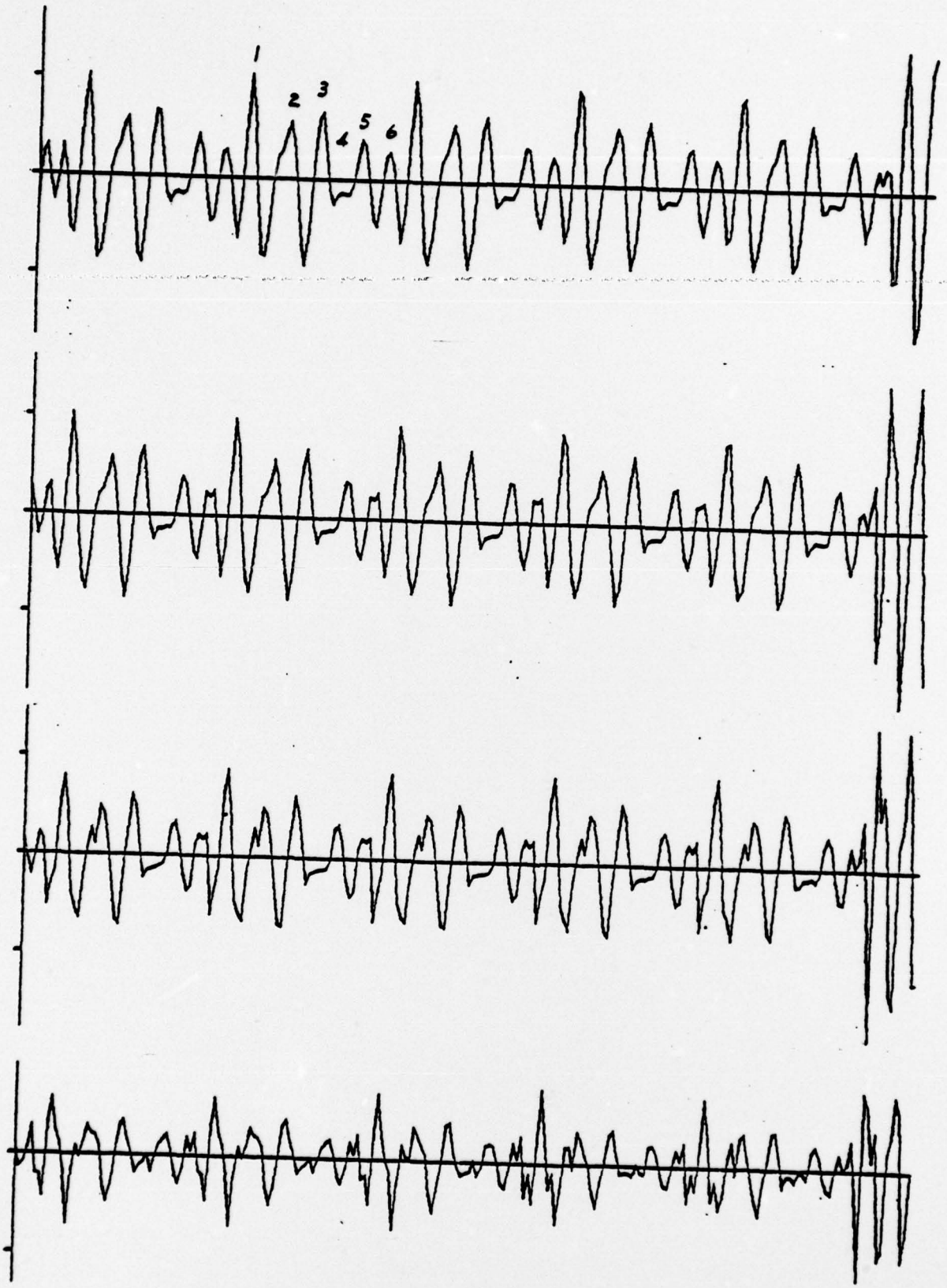
Figure 60. /o/-Segments of the Responses of Four ROC COC2 Channels to the /o/-Segment of Glot-1 Stimulus 4A. The four plots do not have the same scale.

(a) Channel 20 (best frequency = 1111 Hz)

(b) Channel 18 (best frequency = 1492 Hz)

(c) Channel 16 (best frequency = 2000 Hz)

(d) Channel 14 (best frequency = 2500 Hz)


1
2
3
4
5
6

The Vowel /ɛ/

The neuron /ɛ/-POH, the model /ɛ/-POH, and the response of channel 20 to /ɛ/ correlate well (Figure 37). In Figure 61, by channel 16 peak 1 has split into three peaks. There is no evidence in the neural data of these peaks. The conclusion is that any channel lower than channel 18 could not have been used to generate the neural data.

The Vowel /I/

In Figure 42 it was shown that the neuron and model /I/-POH correlated well with each other and the channel 20 response. Figure 62 shows that by channel 18 several of the peaks in a pitch period have been resolved into two or more peaks. There is no evidence for any of these peaks in the neuron /I/-POH. The conclusion is that channel 20 provides the best fit.

The Vowel /u/

Referring to Figures 47 and 63, neural activity occurs at each of the numbered positions in the channel 20 waveform. Therefore, if the displacement model is correct, there should be peaks in the neuron's stimulus at positions 2, 5, and 7. The first channel with a significant peak at position 2 is channel 14. None of the examined channels has a peak at position 5. The neural activity associated with position 7 is very low, suggesting that the peak seen by the neuron has a small magnitude. Through channel 14 there is a peak at this position, but it never becomes significantly greater than zero.

The conclusion for the vowel /u/ is that no channel examined will provide the needed improvement in the stimulus.

The Vowel /i/

Figure 52 shows neural activity at peaks 1, 2, 3, and 5 of the channel 20 response. This is in good agreement with the channel 20

response. In Figure 64 even channel 18 has high frequency activity that is not evident in the neuron /i/-POH. Channel 20 provides the best fit to the neural data.

Conclusion

Although results for other vowels, /ɹ/ and /a/ for instance, would have been better if a high frequency channel were used as the stimulus, the results associated with vowels /ɛ/, /I/, and /i/ suggest that the higher frequency channels will not provide a consistently better match to the neural data. Generally, no channel consistently provides a better fit to the neural data than channel 20.

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Figure 61. /ɛ/-Segments of the Responses of Four ROC COC2 Channels to the /ɛ/-Segment of Glot-1 Stimulus 4A. The four plots do not have the same scale.

(a) Channel 20 (best frequency = 1111 Hz)

(b) Channel 18 (best frequency = 1492 Hz)

(c) Channel 16 (best frequency = 2000 Hz)

(d) Channel 14 (best frequency = 2500 Hz)

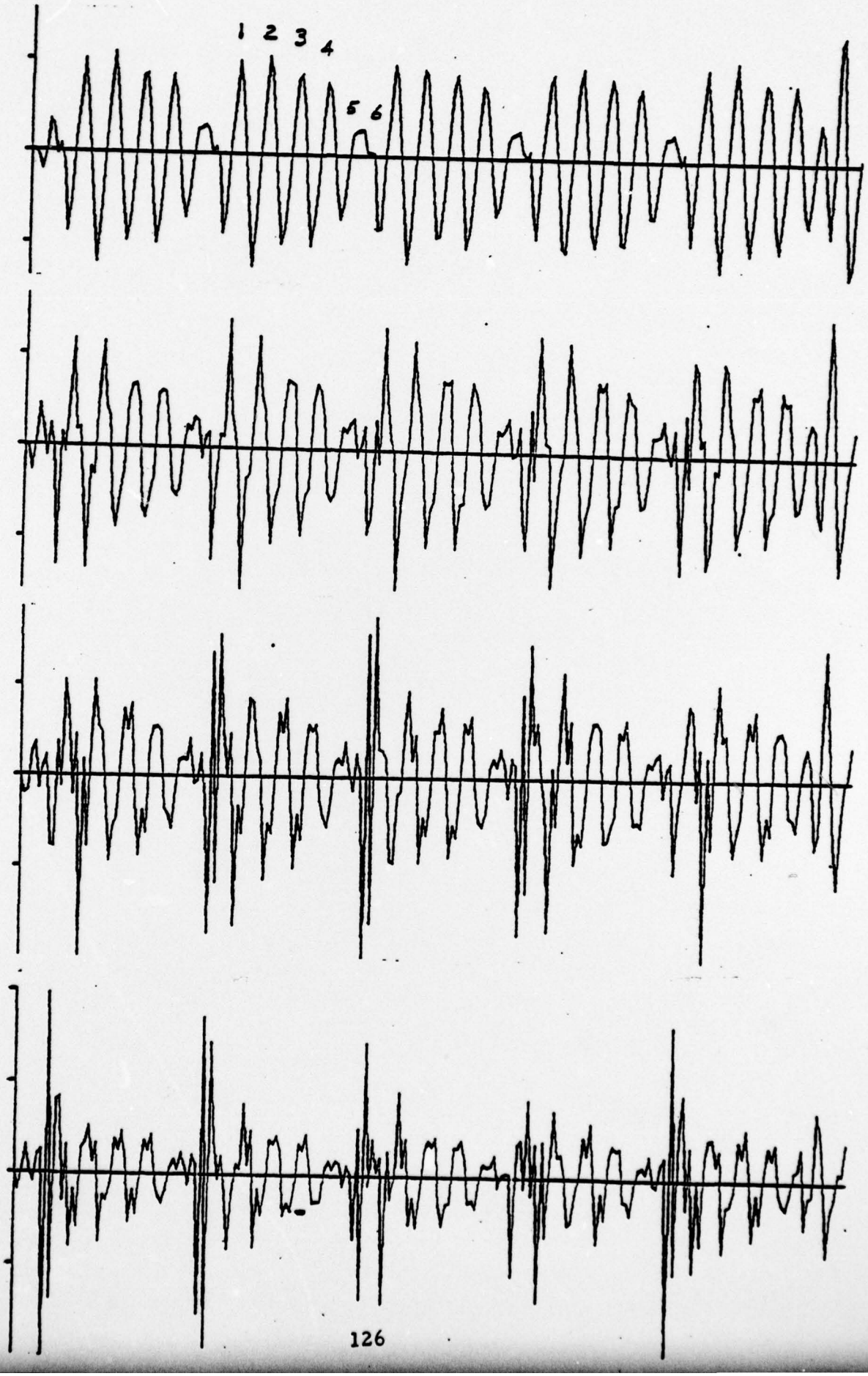

1
2
3
4
5
6

Figure 62. /I/-Segments of the Responses of Four ROC COC2 Channels to the /u/-Segment of Glot-1 Stimulus 4B. The four plots do not have the same scale.

(a) Channel 20 (best frequency = 1111 Hz)

(b) Channel 18 (best frequency = 1492 Hz)

(c) Channel 16 (best frequency = 2000 Hz)

(d) Channel 14 (best frequency = 2500 Hz)

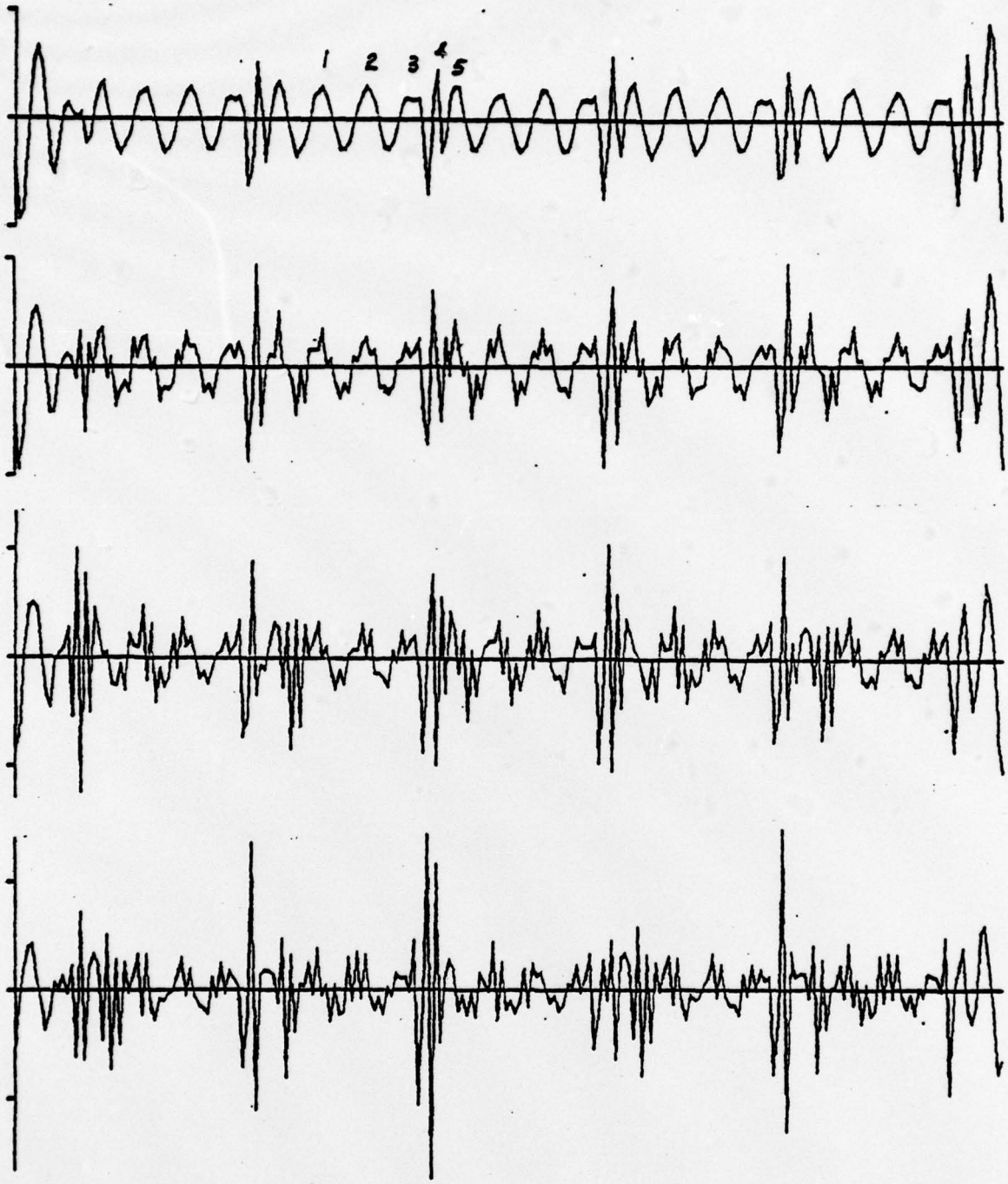

1
2
3
4
5

Figure 63. /u/-Segments of the Responses of Four ROC COC2 Channels to the /u/-Segment of Glot-1 Stimulus 4B. The four plots do not have the same scale.

(a) Channel 20 (best frequency = 1111 Hz)

(b) Channel 18 (best frequency = 1492 Hz)

(c) Channel 16 (best frequency = 2000 Hz)

(d) Channel 14 (best frequency = 2500 Hz)

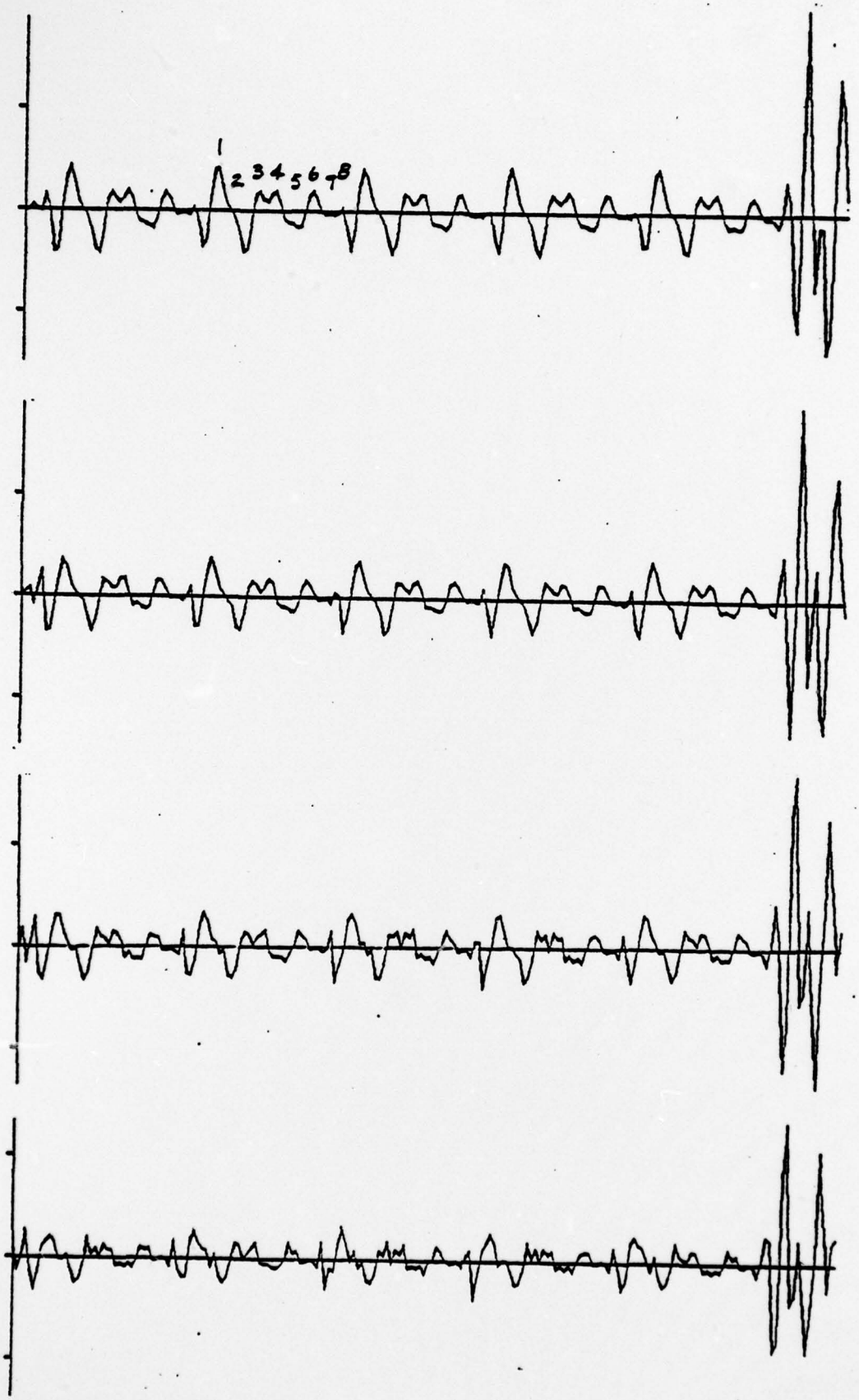

1
2
3
4
5
6
7
8

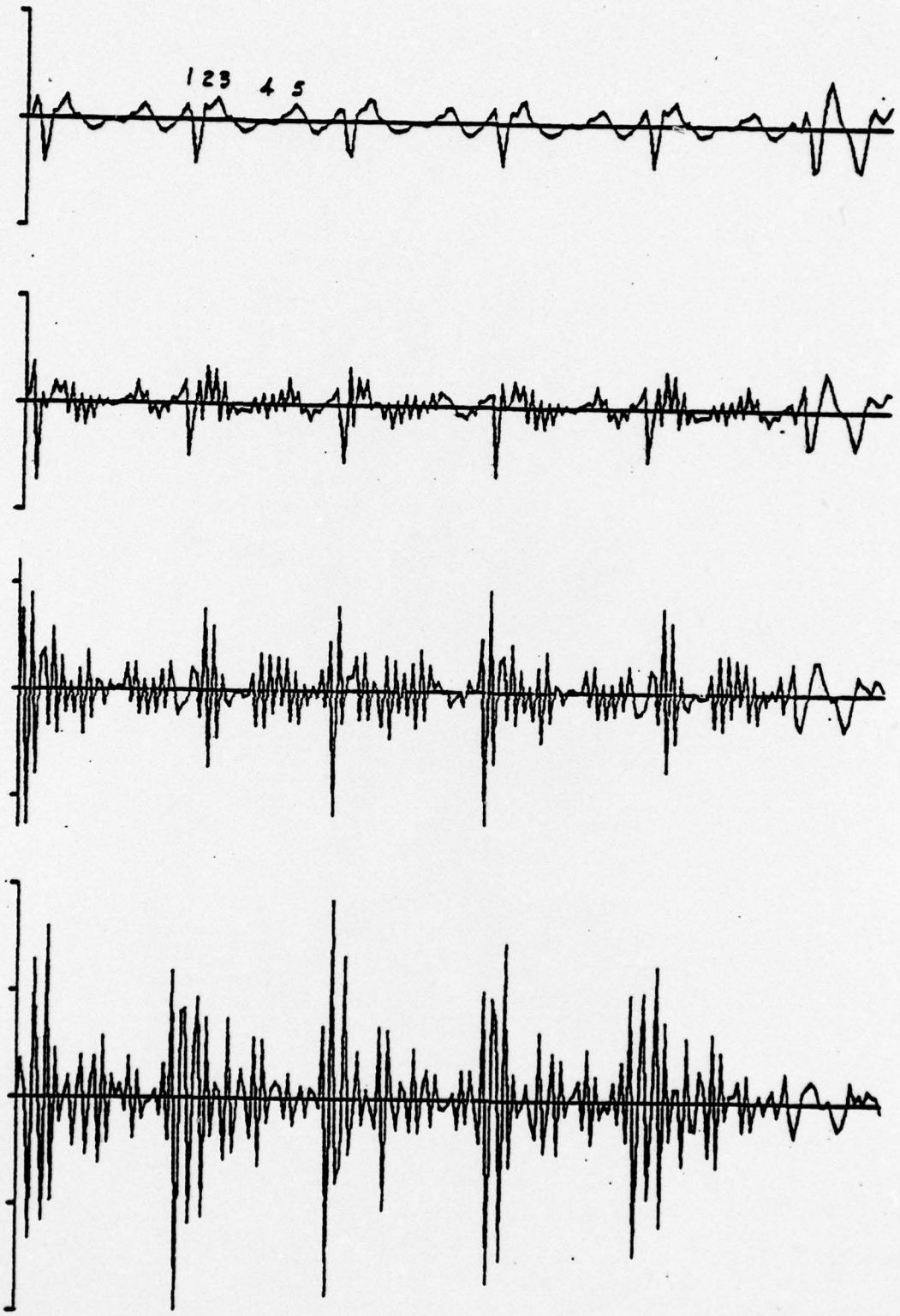
Figure 64. /i/-Segments of the Responses of Four ROC COC2 Channels to the /æ/-Segment of Glot-1 Stimulus 4B. The four plots do not have the same scale.

(a) Channel 20 (best frequency = 1111 Hz)

(b) Channel 18 (best frequency = 1492 Hz)

(c) Channel 16 (best frequency = 2000 Hz)

(d) Channel 14 (best frequency = 2500 Hz)


1 2 3
4 5

4.3 EXAMINATION OF THE MIDDLE EAR TRANSFER FUNCTION

The vowel responses of any ROC COC2 output channel can be modified through the appropriate modification of the middle ear transfer function. For instance, if the transfer function used for the ROC COC2 middle ear circuit was modified so that its peak gain occurs at 4 KHz instead of the current 2 KHz (Figure 2), the response of channel 20 would be expected to have slightly greater magnitude in the high frequency components of the signal.

Zwislocki (1963) has developed a hardware circuit model of the middle ear. The transfer characteristic for this circuit is defined in Figure 65. The characteristic has 6 dB skirts on both the high and low frequency sides and a peak gain at between 1 and 2 KHz. Figure 65 also shows data derived from the cochlear microphonics of two guinea pigs. These data suggest some confusion in the intensity characteristic in the frequency range of interest, 2 to 8 KHz.

In summary, the current middle ear circuit, which has a 12 dB skirt on the low frequency side of its transfer characteristic, is already a possibly significant modification from Figure 65. The existing neurophysiological data leave a possibility that the middle ear transfer function of guinea pig 710827/11 had a peak at 4 KHz or better, but the possibility is remote and probably does not justify modification of the analog middle ear circuit.

4.4 RECOMMENDATIONS TO ACCEPT THE CURRENT MODEL PENDING DEVELOPMENT OF COCHLEAR NUCLEUS MODELS

The overall appearance of the model vowel-POH is acceptable to the author. There are two basic classes of differences between the neuron and model vowel-POHs. The first class is the shape of the individual vowel-POH peaks. The peaks in the neuron vowel-POHs tend to be broader than corresponding peaks in the model vowel-POH. In addition, the maximum within a peak in a model vowel-POH almost always occurs in the first sample

interval of that peak. This is not true of the neuron's behavior.

The second class is the position of the individual peaks, which was discussed in the previous sections of this chapter.

The opinion of the author is that modification of the model to eliminate these differences would be difficult. Noise would probably have to be added to the ROC COC response or the threshold function to obtain the neuron's vowel-POH peak shape. It is not clear what modification should be made to obtain the correct position of individual peaks. The author's opinion is that the problem lies in the middle ear function. In order to obtain the most accurate model, it will be necessary to perform the neurophysiological experiments again, with the individual guinea pigs middle ear transfer function being measured and incorporated in the model.

It is the conclusion of the author that these modifications should not be implemented at this time. Instead, resources sould be directed toward modeling the next level of the auditory system, the cochlear nucleus.

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Zwislocki, J., "Analysis of the Middle-Ear Function", Part II: Guinea-Pig Ear", J. Acoust. Soc. Am., 35, 1034, (1963).